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AFRPL-TR-66-80

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(Unclassified Title)

DEVELOPMENT AND TEST
OF HIGH ENERGY
SOLID PROPELLANTS

TECHNICAL REPORT AFRPL-TR-66-80
APRIL 1966

D D C

HERCULES POWDER COMPANY
INCORPORATED
BACCHUS WORKS   MAGNA,   UTAH

MAY 2 1966

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AIR FORCE ROCKET PROPULSION LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
EDWARDS, CALIFORNIA

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26 April 1966

IN REPLY
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Rocket Propulsion Laboratory
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California

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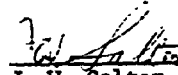
Subject: Development and Test of High Energy Solid Propellants (U),
Report No. AFRPL-TR-66-80, Dated April 1966

Reference: Contract AF 04(611)-10754, Exhibit B, Paragraph 2.1

Gentlemen:

In accordance with Contract AF 04(611)-10754, three copies of
the subject report are hereby submitted.

Very truly yours,

J. W. Salter
Contract Support

JWS:AFeurer:vib

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DEVELOPMENT AND TEST OF
HIGH ENERGY SOLID PROPELLANTS

HERCULES POWDER COMPANY
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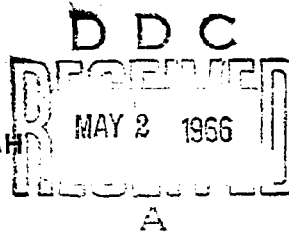
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FOREWORD

This is the third quarterly report under Contract AF 04(611)-10754.
This report was prepared by the Propellant Development Group, Bacchus
Works, Chemical Propulsion Division, Hercules Powder Company. The report
was written by R. F. Keller, J. L. Judkins, and G. R. Gibson, and approved
by J. W. Schowengerdt and Dr. R. L. Schaefer.

Preparation of this report is authorized under Contract
AF 04(611)-10754, in accordance with Exhibit B, paragraph 2.1.

This report is classified confidential to protect a compilation of
information, or a complete analysis of the subject, from individually
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Publication of this report does not constitute Air Force approval
of the report's findings or conclusions. It is published only for the
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The cognizant Air Force Officer is K. W. Joffs, First Lieutenant,
RPMC, Edwards Air Force Base, California.

CONFIDENTIAL ABSTRACT

The objective of this contract is to conduct theoretical and experimental investigations resulting in the demonstration of beryllium hydride (LMH-2) solid propellants delivering in excess of 280 lbf-sec/lbm at standard conditions. The program consists of three tasks: Task I, Analysis and Data Correlation; Task II. Formulation and Ballistic Evaluation; and Task III, Advanced Concepts.

During the first quarter, data correlations were completed under Task I and LMH-2 formulations were designed which were predicted to meet the program objective. In addition, beryllium analog formulations of the proposed LMH-2 systems were also designed for formulation screening.

Under the Task II effort during this quarter, thirty-four 15-lb castings and fifty-one firings of the beryllium formulations were made completing the bulk of the beryllium efficiency studies. Results of this testing confirm the earlier correlations showing high oxidation ratio and high flame temperature to be significant factors in obtaining good efficiency with beryllium propellants. The highest efficiencies obtained (93.6 percent) were from the VIK formulation containing 15.5 percent Be and having a flame temperature of $4109°$ K and an oxidation ratio of 1.27. Low-metal (10 to 12 percent Be) AP/HMX systems showed no loss in efficiency with decreasing pressure, whereas high-metal (14 to 15.5 percent Be) AP systems showed efficiency losses with decreasing pressure. Decreasing the nozzle approach angle and reducing AP particle size improved the efficiency of Be propellants.

Six LMH-2 castings of VIY formulation (17 percent LMH-2) were successfully completed. Three of the grains contained wax-treated LMH-2 and three contained AP-treated LMH-2.

One LMH-2 firing of the VIY formulation (17 percent wax-treated LMH-2) gave a delivered Isp_{1000}^{15} value of 278.6, and one firing of VIY with AP-treated LMH-2 gave an Isp_{1000}^{15} value of 275.4. Both firings were made at relatively low L* values ($\sim$120).

Vacuum baking and air desorption were found to be necessary to eliminate porosity from propellants made with "as received" LMH-2. Vacuum baking coupled with wax treating or AP treating were also effective means of eliminating porosity.

AP treating and wax treating continued to be effective means of improving processibility of LMH-2 propellants.

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Abbreviation	Meaning
2-NDPA	2-Nitrodiphenylamine
15PC	15-pound charge
AL	Aluminum
AN	Ammonium nitrate
AP	Ammonium perchlorate
Be	Beryllium
BeO	Beryllium oxide
CMDB	Composite modified double-base
DTA	Differential thermal analysis
ESD	Electrostatic discharge
FPC	40-pound charge
HMX	Cyclotetramethylene tetranitramine
K	Kelvin
LMH-2	Beryllium hydride
NG	Nitroglycerin
PNC	Plastisol nitrocellulose
P-K-r	Pressure-K-burning rate
RES	Resorcinol
TA	Triacetin
TAGN	Triaminoguanidine nitrate
TFLN	Teflon
VCP	Be/HMX propellant formulation

SECTION I

INTRODUCTION

A. OBJECTIVE

The objective of this program is to conduct theoretical and experimental investigations resulting in the demonstration of beryllium hydride (IMH-2) solid propellants delivering a specific impulse in excess of 280 lb-sec/lb at standard conditions.

Solid propellants containing IMH-2 have a theoretical specific impulse up to 30 sec greater than that of beryllium-containing propellants. Thus far the firings of test motors containing IMH-2 propellants have not yielded the expected gain in delivered specific impulse. Motor and propellant parameters of chamber temperature, chamber pressure, mass flow rate, expansion ratio, oxidation ratio, oxidizer particle size, hydride content, metal/hydride ratio, and total metal content have been investigated under various government contracts over the past 2 years. Although much has been learned about IMH-2 propellants during this period, the high specific impulse promised by the hydride has not been realized. More research is required on these propellants before they can be efficiently utilized in large motors.

B. SCOPE

The program is a three-task effort. In task I, the results of previous beryllium and IMH-2 firings will be correlated to define the parameters important for higher delivered impulses. The results of this effort will be applied in task II to formulate and test candidate high-performance propellant systems. The objective of the task III effort will be to use advanced formulation or motor techniques to study and/or improve IMH-2 combustion.

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SECTION II

TASK I, ANALYSIS AND DATA CORRELATION

A. SCOPE

The objective of this task is to evaluate and correlate available beryllium and LMH-2 firings. Particular emphasis will be placed on the correlation of motor efficiency with motor and formulation variables. Theoretical specific impulse calculations will be conducted on a wide variety of formulations to establish the relationship between propellant parameters and theoretical performance of beryllium and LMH-2 propellants. Based on the motor efficiency correlations and theoretical performance calculations, formulations will be designed which are predicted to deliver specific impulse values capable of meeting the program objectives. In addition to the advanced formulation effort, propellants will be investigated to supplement or verify reported data on current beryllium and LMH-2 formulations. The performance of beryllium systems containing high metal levels equivalent to those in high energy LMH-2 systems will also be investigated.

B. DATA CORRELATIONS

As reported in the first quarterly report,[1] a literature survey was conducted and available data on the impulse efficiency of beryllium and LMH-2 motor firings were correlated on the basis of motor and propellant parameters.

In summary, the following factors were found to be important in influencing the motor efficiency of beryllium and LMH-2 propellants:

(1) High flame temperature and high oxidation ratio propellants show no loss in efficiency with decreasing pressure down to 500 psia.

(2) Low flame temperature or low oxidation ratio propellants show loss in efficiency with decreasing pressure. This effect could not be completely separated from mass flow or residence time effects on efficiency.

(3) Both beryllium and LMH-2 propellants show a strong dependence on high flame temperatures for good efficiency.

(4) Oxidation ratio has a strong effect on the efficiency of low temperature beryllium propellants. There is an indication that oxidation ratio is important for LMH-2 efficiency, but only a general trend could be obtained.

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[1]Development and Test of High Energy Solid Propellants, Report No. HPC-230-12-5-1, dated 28 October 1965

(5) Correlations based on total LMH-2 content show a loss in efficiency at high hydride loadings (greater than 15 percent).

(6) More intimate contact of oxidizer and fuel in LMH-2 systems should improve efficiency based on efficiency effects of AP particle size, AP/LMH-2 ratios, and ground LMH-2.

The importance of flame temperature on obtaining good efficiencies with beryllium and LMH-2 propellants is illustrated in Figures 1 and 2, respectively.

C. FORMULATION AND TEST DESIGN

The correlations show several areas in which further investigation is needed before reliable predictions can be made for the performance of both beryllium and LMH-2 propellants. In general, the beryllium correlations are significantly better than for LMH-2 systems. Additional beryllium testing is still needed in the following areas for further clarification of propellant parameters on impulse efficiency:

(1) High metal levels (> 15.5 percent) at high flame temperatures and oxidation ratios

(2) High metal levels and high flame temperatures at low oxidation ratios

(3) Evaluation of oxidizers different from AP and HMX, such as AN and TAGNO$_3$

(4) Additional testing at high oxidation ratios and high flame temperatures for determining the effect of AP particle size

Further testing is also needed in the following areas for clarification of motor parameters:

(1) Optimization of nozzle geometry at high metal levels

(2) Increased L* studies for both efficient and inefficient beryllium propellants and LMH-2 propellants

For LMH-2 systems, the following testing is needed to clarify propellant parameters:

(1) High LMH-2 loadings at flame temperatures in excess of 3600° K and at high oxidation ratios

(2) Comparative evaluation of AP, AN, and HMX oxidizers

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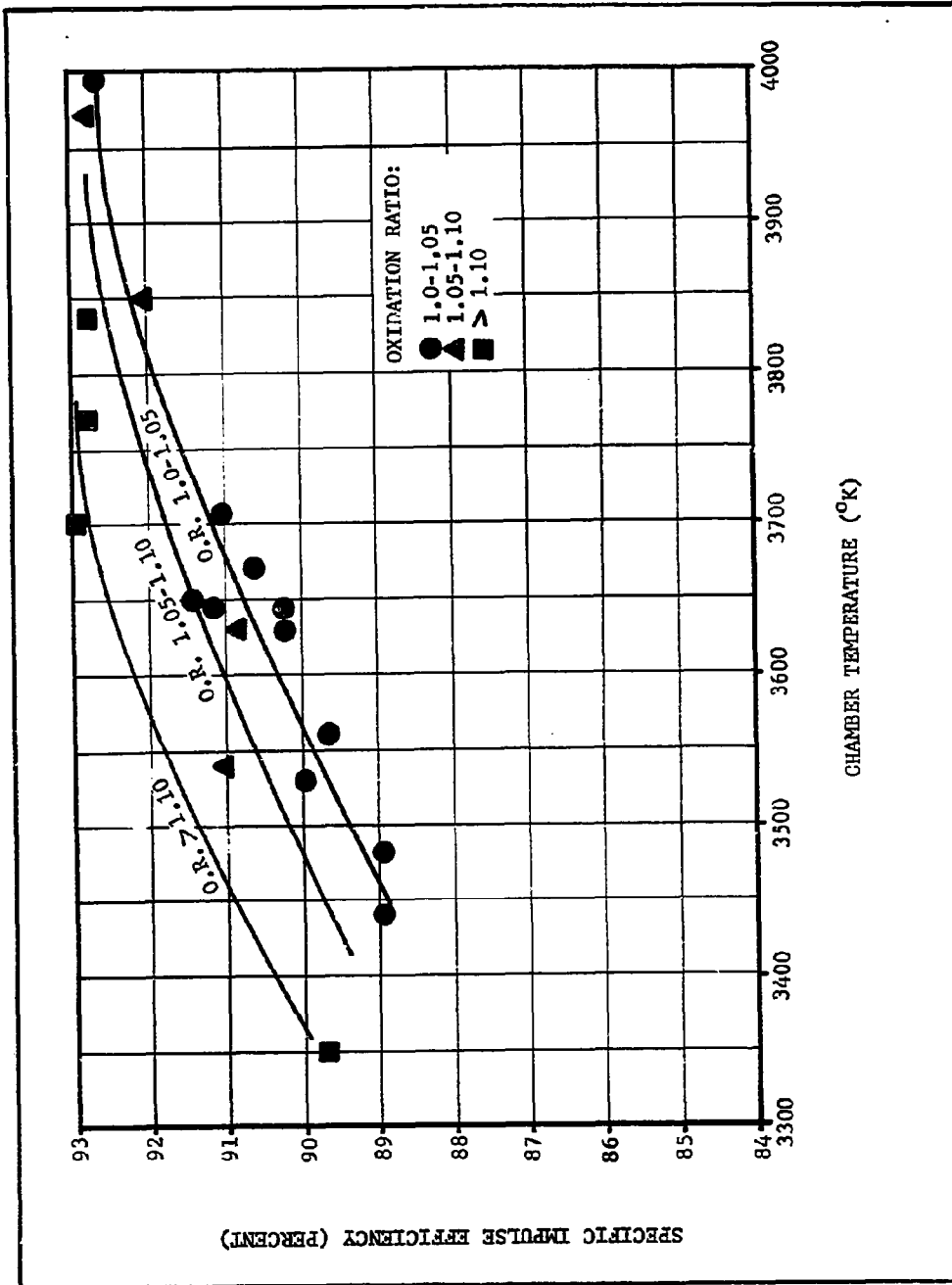
Figure 1. Effect of Chamber Temperature and Oxidation Ratio on Specific Impulse Efficiency of Beryllium Propellants

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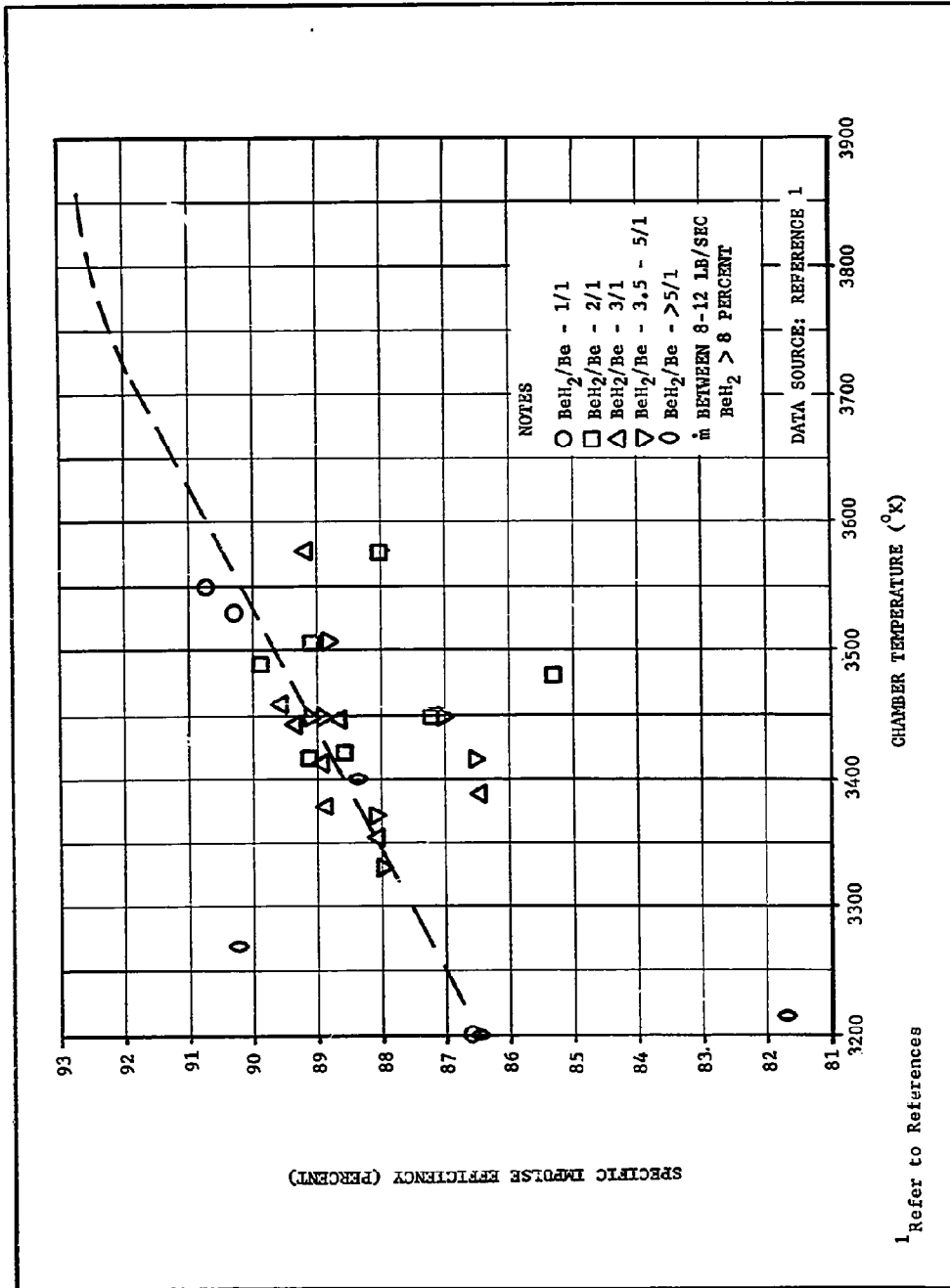
Figure 2. Effect of Chamber Temperature on Specific Impulse Efficiency for LMH-2 Propellants

(3) More intimate contact between oxidizer and LMH-2

(4) Addition of fluorine to LMH-2 as a combustion aid

The Task II and Task III effort is designed to clarify these areas for beryllium and LMH-2 propellants.

Table I shows a list of the beryllium formulations chosen for testing to better define the effect of propellant parameters on performance. VIH propellant was designed to have the same metal level and oxidation ratio as the proposed 19-percent LMH-2/AP formulation. VII was formulated to demonstrate the effect on efficiency due to decreasing oxidation ratio in a high metal level propellant. VLJ was formulated to show the effect on efficiency of the AP:Be ratio at a constant metal level, flame temperature, and oxidation ratio. VLJ was also formulated with 45μ and 180μ AP to demonstrate the effect of AP particle size on impulse efficiency thus providing the performance trade-off between AP particle size and LMH-2 loadings necessary to optimize delivered impulse. VIK, VIL, VIM, and VIN represent the beryllium analogs of the 17 percent LMH-2, AP; 15 percent LMH-2, AP, HMX; 19 percent LMH-2, AN; and 17 percent LMH-2, AN formulations, respectively, in both metal level and oxidation ratio. VIO was designed to determine the effect of oxidation ratio on efficiency at low metal levels, and VIG was formulated to evaluate TAGNO3 as an oxidizer.

Based on the theoretical calculations and using the temperature correlation derived in Figure 2, six candidate LMH-2 formulations were chosen which are designed to confirm the expected efficiency envelope and to attain the program objective of a demonstrated $I_{sp} \geq 280$ sec. Table II contains the LMH-2 propellants together with the theoretical and predicted performance values.

Additional testing to determine the effect of motor parameters on the performance of beryllium and LMH-2 propellants will also be accomplished in Task II as follows:

Motor Parameter	Formulation	Number of Firings
Nozzle Approach Angle		
15° Approach	VCP	2
15° Approach	VLJ	4
5° Approach	VCP	2
5° Approach	VLJ	4
High L*	VCP	2
High L*	VII	2
High L*	VIY	10

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TABLE I

BERYLLIUM PROPELLANTS FOR FORMULATION SCREENING

Formulation	Be (wt %)	Oxidizer Type	I_{sp} (sec)	T_c (°K)	O.R.*	Number of Firings**		Purpose
						1000 psi	500 psi	
VGP	10	HMX/AP	283	3840	1.22	3	3	Control
VIH	15.5	AP	278	4173	1.17	3	3	LMH-2 19% Analog with respect to TM*** and O.R.
VII	15.5	AP	279	3971	1.05	3	3	LMH-2 19% Analog with respect to TM; lower O.R.
VIJ	15.5	AP	277	4145	1.17	3	--	Total AP effect
VIK	14.0	AP	277	4109	1.27	3	3	LMH-2 17% Analog TM and O.R.
VIL	12.0	HMX/AP	281	4008	1.24	3	3	LMH-2 15% Analog AP/HMX with respect to TM and O.R.
VIM	15.5	AN	281	3820	1.17	3	3	LMH-2 19% Analog with respect to TM and O.R.

*, **, ***, See end of table

TABLE I (Cont)

BERYLLIUM PROPELLANTS FOR FORMULATION SCREENING

Formulation	Be (wt %)	Oxidizer Type	Isp (sec)	T_c (°K)	O.R.*	Number of Firings** 1000 psi	Number of Firings** 500 psi	Purpose
VIN	14.0	AN	279	3744	1.28	3	3	LMH-2 17% Analog with respect to TM and O.R.
VIO	8.0	HMX/AP	281	3745	1.38	3	--	O.R. effect at low TM
VIG	12.5	TAGNO₃/AP	291	3633	1.02	3	--	Evaluate TAGNO₃
						30	21	

*O.R. = Oxidation Ratio

**Optimum expansion ratio at Bacchus ambient

***TM = Total metal level

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TABLE II

IMH-2 PROPELLANTS FOR FORMULATION SCREENING

Propellant Type	Binder Level (wt %)	Oxidizer (wt %)	IMH-2 (wt %)	I^o_{1000} (sec)	T_c (°K)	O.R.*	Impulse Efficiency Range	Predicted I_{sp} Del (H)**	Predicted I_{sp} Del (L)***
VIX	62	AP	15	304	3678	1.34	90.7-91.6	279	276
VIY	62	AP	17	309	3679	1.22	90.7-91.6	283	280
VIZ	62	AP	19	314	3671	1.11	90.6-91.5	287	285
--	62	AP/HMX	15	307	3636	1.23	90.2-91.2	280	277
VJA	62	HMX	15	309	3621	1.15	90.0-91.1	282	278
--	62	AN	17	309	3529	1.25	88.6-90.4	279	274

*Oxidation Ratio
**(H) High value expected
***(L) Low value expected

D.   PROGRAM DATA ANALYSIS

    1.   Beryllium Firings

         During the third quarter, the bulk of the scheduled beryllium
15PC motor firings were completed and analysis of the resulting data was
initiated.

         The following parameters were considered:

              (a) Propellant parameters:

                   (1) Flame temperature

                   (2) Oxidation ratio

                   (3) Metal level

                   (4) AP particle size

              (b) Motor parameters:

                   (1) Chamber pressure

                   (2) Mass flow rate

                   (3) L*

                   (4) Nozzle approach angle

         A complete summary of individual firings is given in Section III.
Table III contains a summary of these data. A least squares analysis was
performed on the beryllium efficiency firings for chamber pressure effects.
(The data from this analysis are summarized in Table III.) This analysis
allowed accurate comparison of all propellants tested at 1000 psia chamber
pressure. In addition, efficiencies for the selected propellants speci-
fically tested for pressure effects are summarized at 500 psia. Conclusions
based on these data are contained in the following subparagraphs.

              (a) Be/AP/HMX Propellants

                   With Be/AP/HMX propellants, the highest efficiency
at 1000 psia was 93.6 percent, which was obtained with the high temperature
(4109° K) and high oxidation ratio (1.27) propellant, VIK. Increasing
the oxidation ratio to 1.38 with a decrease in metal level and flame tem-
perature decreased efficiency to 92.6 percent (VIO firings). Decreasing
the oxidation ratio to 1.05 at constant flame temperature decreased the
efficiency to 91.0 percent (VII firings). All of the Be/AP/HMX firings
appeared to fit the same generalized temperature and oxidation ratio rela-
tionship with impulse efficiency developed in the first quarter's work.

TABLE III

BALLISTIC PERFORMANCE SUMMARY

Formulation	Percent Be	Oxidizer	T_c[1] (°K)	OR[2]	P_c[3] (psia)	$\dot{m}$[4]	No. of Firings	Efficiency (%)	I_{sp1000}[1,5] (lbf-sec/lbm)	Efficiency vs P_c
Efficiency Studies										
VCP	10.0	AP/HMX	3850	1.22	500	7.9	3	92.01	260.4	
					1000	8.2	3	91.69	259.5	92.34 - 0.00065 P_c
VIJ	15.5	AP	4145	1.17	500	8.2	3	92.27	256.0	
					1000	8.6	2	92.88	257.7	91.67 + 0.00121 P_c
VIH	15.5	AP	4173	1.17	1000	11.3	3	93.36	259.5	92.36 + 0.00100 P_c
VII	15.5	AP	3971	1.05	500	6.9	3	90.71	252.8	89.87 + 0.00169 P_c
VIK	14.0	AP	4109	1.27	1000	6.4	3	91.56	255.2	
					500	11.3	3	92.84	256.7	92.08 + 0.00151 P_c
VIL	12.0	AP/HMX	4008	1.24	1000	11.2	3	93.60	258.8	
					500	12.0	3	92.99	261.4	93.43 - 0.00089 P_c
VIO	18.0	AP/HMX	3758	1.38	1000	12.2	3	92.54	260.1	91.94 + 0.00065 P_c
VIG	12.5	AP/TAGNO3	3633	1.02	1000	8.4	3	92.59	260.3	88.79 - 0.00029 P_c
VIN	14.0	AN	3744	1.28	1000	6.8	3	88.50	237.3	
					1000	4.4	3	87.99	245.1	82.69 + 0.00530 P_c
AP Particle Size										
VIJ-5021[a]	15.5	AP	4145	1.17	810	6.8	3	92.19	255.7	
VIJ-5031[b]	15.5	AP	4145	1.17	800	8.2	2	92.70	257.1	
VIJ-5061[c]	15.5	AP	4145	1.17	760	9.0	2	93.24	257.4	
Nozzle Contouring										
VCP[d]	10.0	AP/HMX	3850	1.17	970	7.7	2	92.28	261.2	
[e]					1050	8.2	2	92.36	261.4	
[f]					1000	8.2	3	91.69	259.5	
VIL[d]	15.5	AP	4145	1.17	970	8.0	3	93.77	260.1	
[e]					1040	8.4	3	93.41	259.1	
[f]					1000	8.6	2	92.88	257.7	

Notes:
1 T_c = Chamber temperature
2 OR = Oxidation ratio
3 P_c = Chamber pressure
4 $\dot{m}$ = Mass flow rate
5 Least squares analysis for pressure dependence

a = 180 μAP
b = 90 μAP normalized to 800 psia
c = 45 μAP
d = 5° approach angle
e = 15° approach angle
f = 30° approach angle

(See Figure 1.) The effect of flame temperature and oxidation ratio on efficiency is shown in Figure 3. As noted from the VIO firings, high efficiencies can still be maintained at lower flame temperature by increasing the oxidation ratio. An extension of the data obtained from the Task II firings to the previous Figure 1 correlation is shown in Figure 4. As shown the Task II firings confirm the original correlation.

(b) Metal Level Effect

No effect of metal level on impulse efficiency could be determined at the high pressure level, with the highest efficiencies being obtained at 15.5 percent beryllium. Because of the strong flame temperature dependence on metal loading coupled with the efficiency-temperature-oxidation ratio effect, any metal level effect would probably be obscured.

(c) VCP, VII, VIJ, VIK, and VIL Propellants

The five propellants, VCP, VII, VIJ, VIK, and VIL, were specifically tested for pressure effects. The correlations reported in Report No. HPC-230-12-5-1 had indicated that the high-flame-temperature, high-oxidation-ratio propellants showed little or no efficiency loss with decreasing pressure. It was not possible in this initial correlation to separate the added effects of mass-flow rate and L^*. In this program, the mass-flow rate was held essentially constant for a given propellant at two pressure levels. The effect of chamber pressure on impulse efficiency for the five propellants is shown in Figure 5. As shown the three propellants, VII, VIJ, and VIK, showed efficiency losses ranging from 0.6 to 0.9 percent as the pressure was decreased from 1000 to 500 psia. In contrast the VCP and VIL propellants actually showed a slight increase (0.3 to 0.5 percent) with decreasing pressure. A summary of the important propellant and motor parameters is contained in the following tabulation:

Propellant	Oxidation Ratio	T_c	Be	Oxidizer	$\dot{m}$[1]	L^*[1]	Eff[2]
VCP	1.22	3850	10	AP/HMX	6.7-8.4	130-180	+0.3
VIL	1.24	4008	12	AP/HMX	9.1-12.1	100-150	+0.5
VIJ	1.17	4145	15.5	AP	7.8-9.0	130-180	-0.6
VIK	1.27	4109	14.0	AP	10.1-12.1	86-142	-0.8
VII	1.05	3971	15.5	AP	6.0-8.0	170-260	-0.9

(1) Mass flow and L^* range covered

(2) Efficiency at 500 psia minus efficiency at 1000 psia

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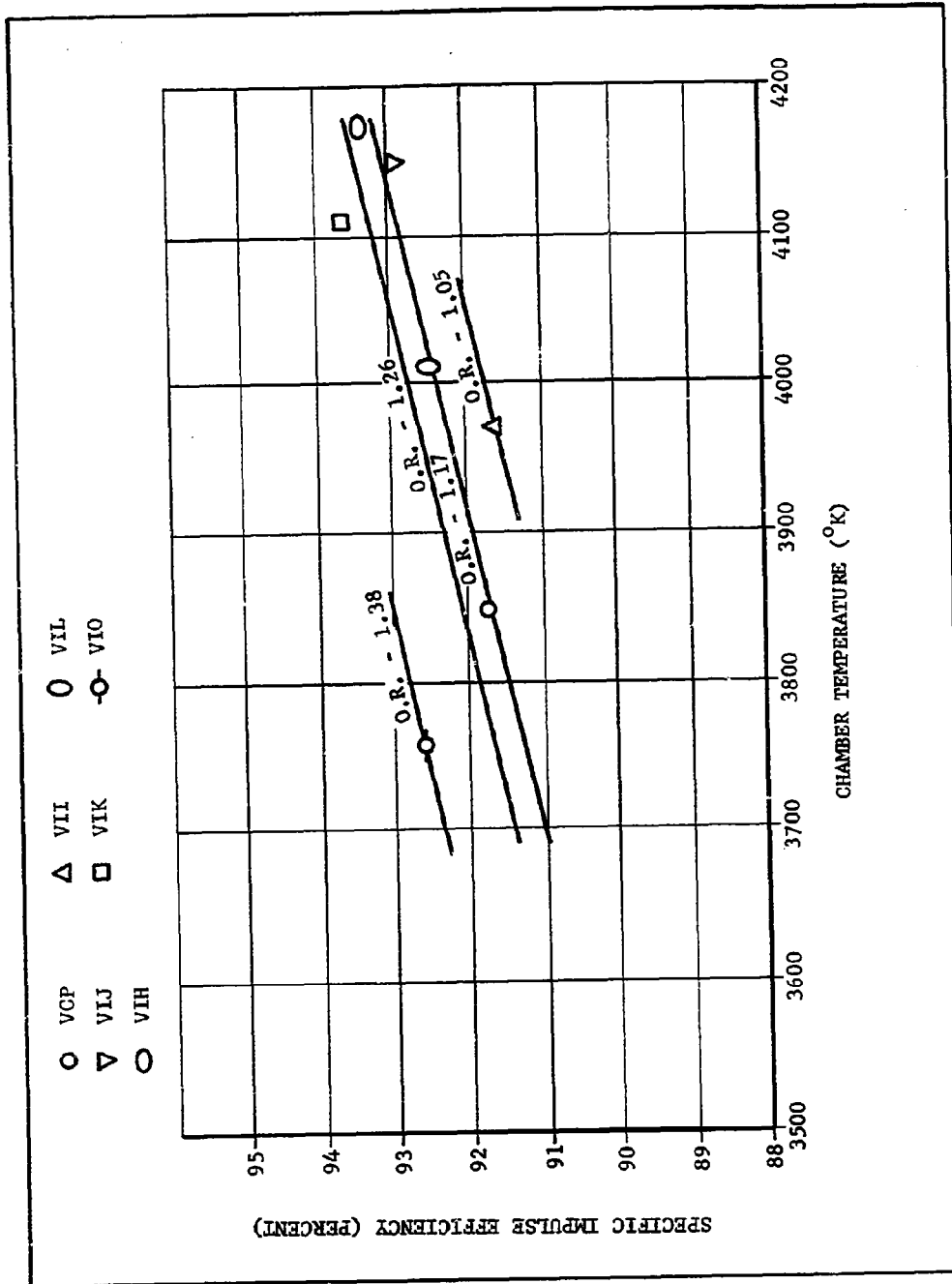
Figure 3. Effect of Chamber Temperature and Oxidation Ratio on Specific Impulse Efficiency of Task II Beryllium Propellants

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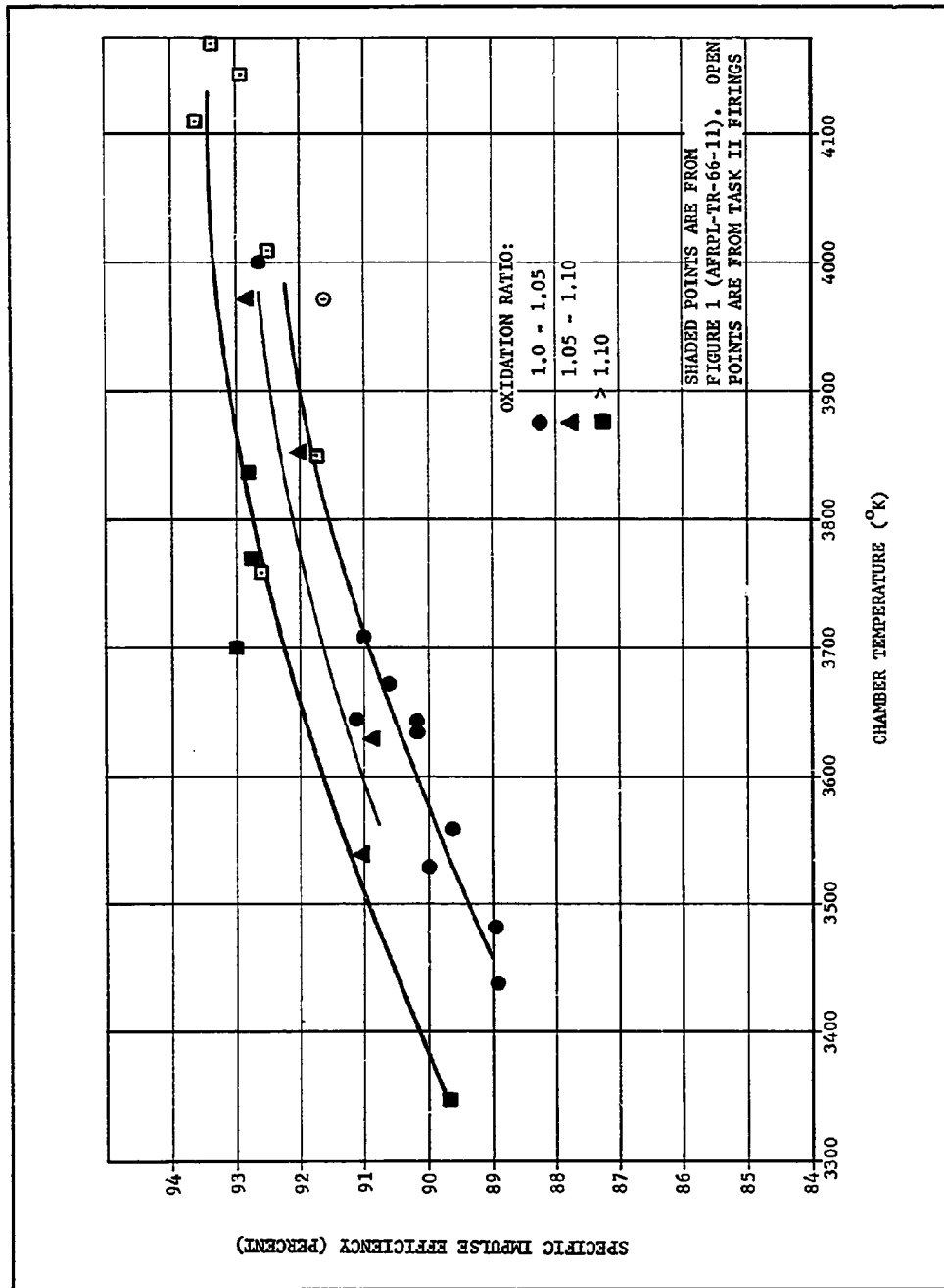
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Figure 4. Effect of Chamber Temperature and Oxidation Ratio on
Specific Impulse Efficiency of Beryllium Propellants
(Revised)
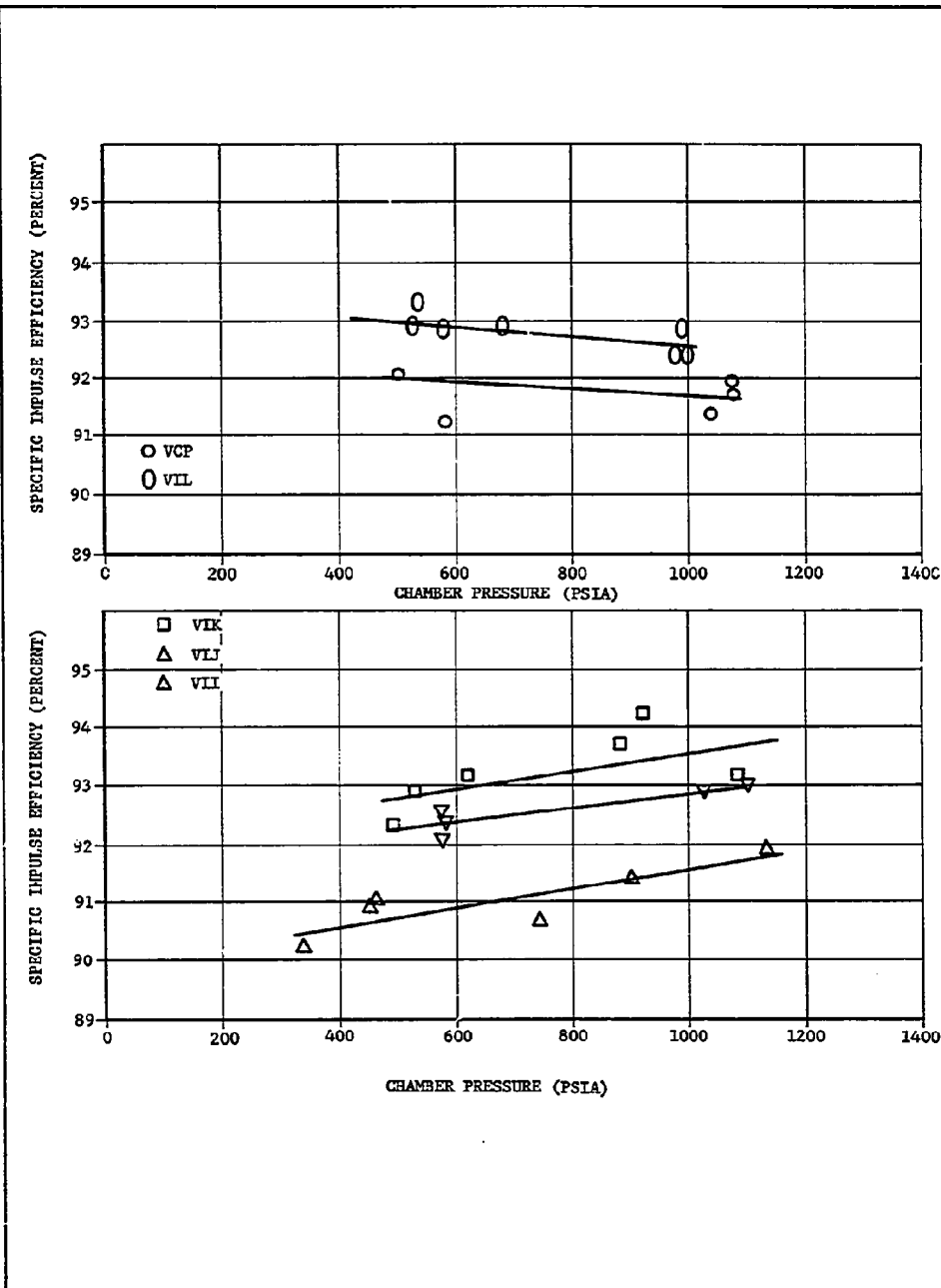
Figure 5. Effect of Chamber Pressure on Specific Impulse
Efficiency of Beryllium Propellants

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As shown, chamber temperature and oxidation ratio had no apparent effect on the pressure effects obtained. Mass-flow rates were maintained over a narrow range for a given propellant, and in addition mass-flow rates overlaped for most propellants. Thus, mass-flow rate is not considered a factor in the pressure effects. This leaves differences in metal level, oxygen source, and L* as possible reasons for the observed pressure effects. Data from other sources will be correlated in an attempt to relate the above variables to the efficiency losses with decreasing pressure.

(d) **Mass Flow Rates**

Figure 6 shows impulse efficiency as a function of mass-flow rate and L* for the propellants tested. All of the firings, with the exception of the low-burning-rate propellant, VIN containing AN, were conducted at mass-flow rates in excess of 6 lb/sec. The efficiency of the control propellant VCP, which shows no pressure effect, remained constant over a mass-flow range of 6 to 8 lb/sec. The efficiency data for the remainder of the propellants were widely scattered on the mass-flow plot with a general trend toward higher efficiencies at the higher mass-flow rates. However, if only high pressure firings are considered, no mass-flow effect is apparent.

The data shown on the L* plot in Figure 6 is also widely scattered. However, certain trends appear to exist. In particular, the three propellants, VIJ, VIK, and VII, which show pressure effects also show strong L* effects. A comparison of the data from this program with the L* relation previously developed as reported in Report No. HPC-230-12-5-1 show the higher temperature and oxidation ratio propellants, VIJ and VIK, maintain high efficiencies at relatively low L* values. In contrast, the high-temperature, low-oxidation-ratio propellant VII showed significant losses at relatively high L* values and approximated the low-temperature and low-oxidation curve, as shown. Two questions remain to be answered to clarify the L* correlation. The first question is whether an increase in L* will increase the efficiency of a propellant showing pressure effects. The second question is whether an increase in L* would increase the efficiency of a propellant showing no pressure effects. Both questions must be answered at constant mass-flow rate and chamber pressure. Firings of VCP and VII are scheduled during the next quarter to clarify these areas.

(e) **Propellants With TAGNO₃ and AN**

The propellants containing TAGNO₃ and AN were significantly less efficient than the Be/AP/HMX formulations. The average efficiency for firings of VIG propellant containing TAGNO was 88.5 percent. For the firings of VIN propellant containing AN, the average efficiency was 88.0 percent. Since the VIN formulation had both a reasonably high flame temperature and high oxidation ratio, the oxygen source is indicated as an important factor. A comparison of the oxygen sources is also available by comparing the VIJ formulation to VIH. Both formulations have the same oxidation ratio and equivalent flame temperatures. However, VIH
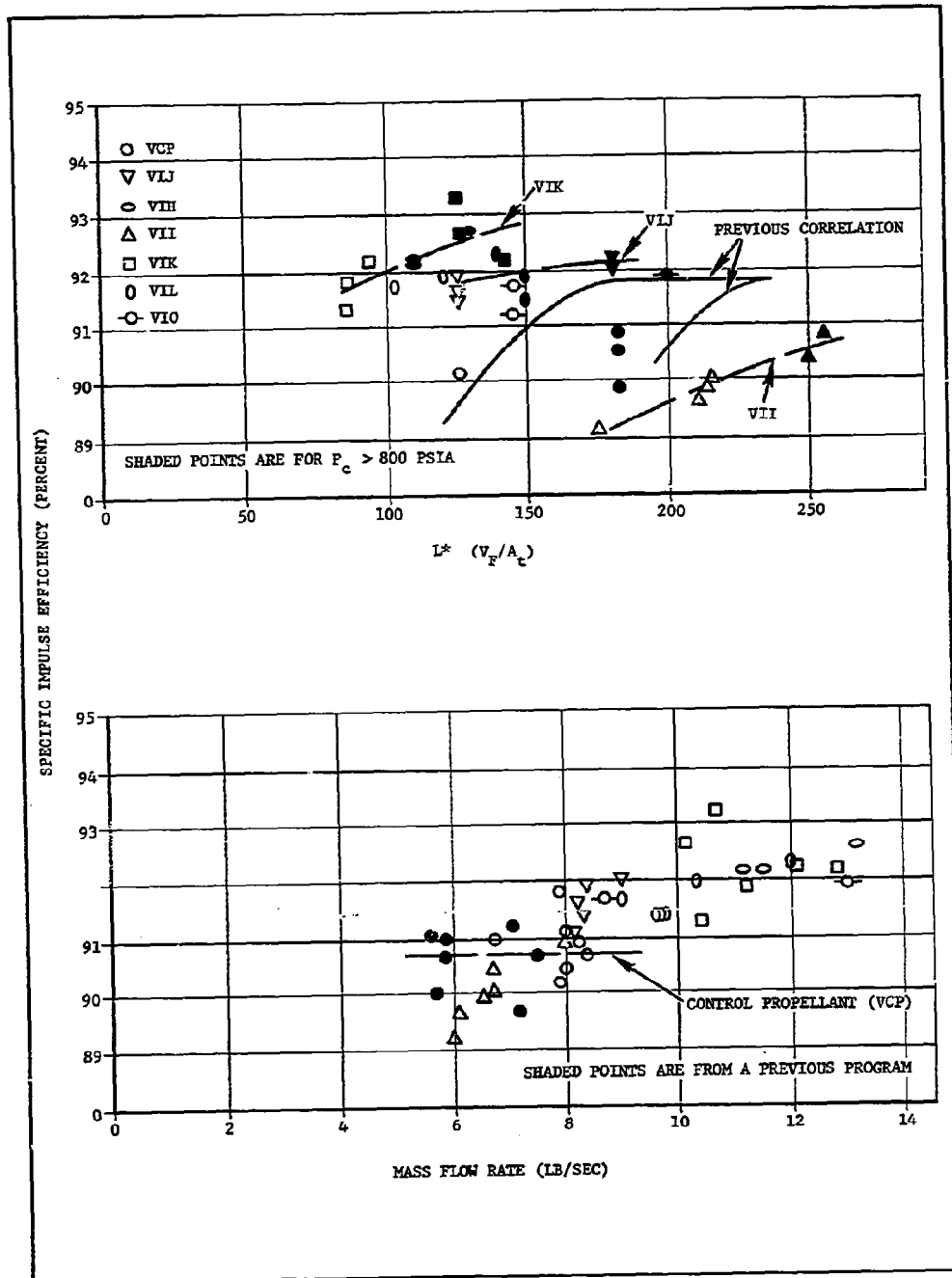
Figure 6. Effect of Mass Flow Rate and L* on Specific Impulse Efficiency of Task II Beryllium Propellants

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containing 5 percent NG in place of AP gave 0.5 percent higher efficiency. Based on these results, a ranking of oxidizer effectiveness would be as follows: NG, AP, HMX, TAGNO$_3$, and AN.

(f) Nozzle Approach Contour Effect

The effect of nozzle approach contour on efficiency for VCP and VLJ is shown in Figure 7. As shown the efficiency increased 0.6 percent for VCP and 0.9 percent for VLJ when the approach angle was reduced from 30 to 5 degrees. Calculations are presently being made to normalize these data for nozzle weight losses. Based on these data, the 15 degree approach appears near optimum and will be used for the IMH-2 firings under the final characterization.
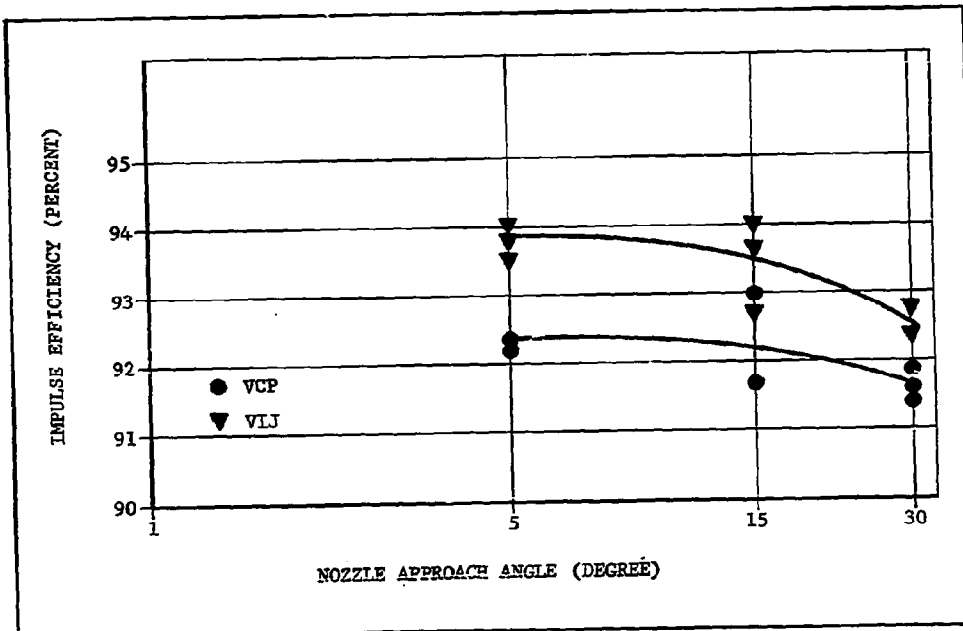
Figure 7. Impulse Efficiency as a Function of
Nozzle Approach Angle

(g) AP Particle Size Effect

The effect of AP particle size on efficiency for the VLJ formulation is shown in Figure 8. The efficiency increased 1.0 percent, from 180 μ to 45 μ AP. All of the IMH-2/AP formulations contain 90 μ AP. These data indicate approximately 0.5 percent increase in efficiency could probably be realized with the IMH-2 formulations if 45 μ AP could be incorporated. Use of 45 μ AP in IMH-2 formulations is not presently possible due to the processibility considerations.

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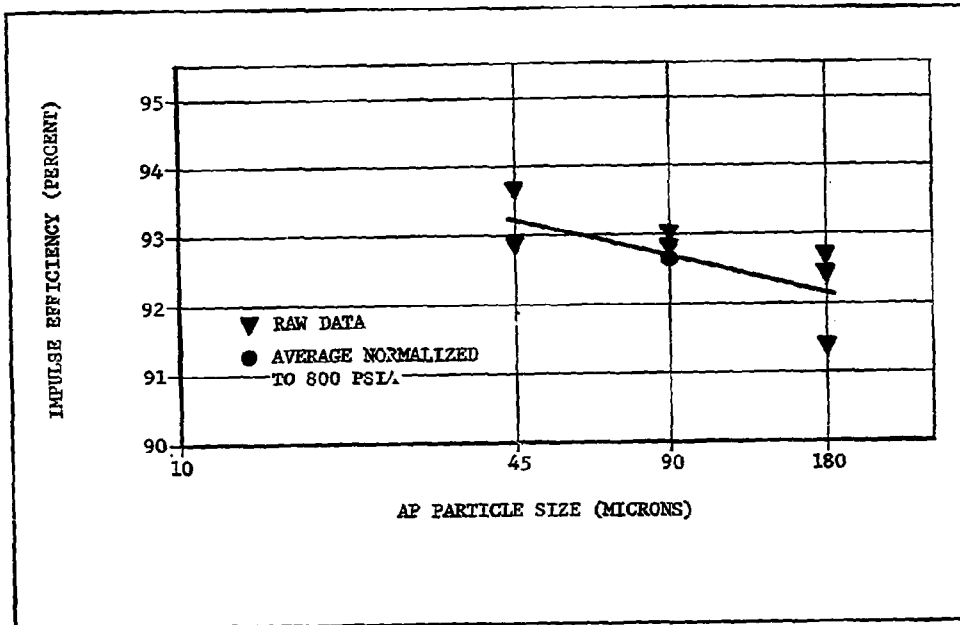
Figure 8. Impulse Efficiency as a Function of AP
Particle Size in VLJ Formulations

2. IMH-2 Firings

Only limited data were available on IMH-2 firings. These data
are shown in the following tabulation:

Formulation	VIY (wax treated)	VIY (AP treated)
IMH-2	17	17
T_c	3678	3678
OR	1.22	1.22
No. firings	1	1
P_c	671	1192
$\dot{m}$	6.71	9.23
L^*	112	130
Efficiency	90.2	89.16
$Isp \, \frac{15}{1000}$	278.6	275.4

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As shown, the delivered impulse of VIY containing wax-treated
LMH-2 was 278.6, only 1.4 sec below target impulse. The efficiency of the
VIY containing AP-treated LMH-2 was approximately 1 percent less than the
wax material, as predicted by the combustion bomb shown in Report No.
AFRPL-TR-66-11. The efficiency of the VIY formulation was approximately
1 percent lower than predicted from the beryllium correlation in Figure 3.

During the next quarter, LMH-2 firings of the selected propellants
should provide the formulation and motor guidelines necessary to optimize
delivered impulse and meet the program objectives. Correlation studies
will be continued with beryllium and LMH-2 systems as additional data be-
come available.

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SECTION III

TASK II, FORMULATION AND BALLISTIC EVALUATION

A. SCOPE

Task II will comprise the majority of the program effort. The objective of this task is to formulate and test candidate high-performance propellant systems selected under Task I. This task will utilize both beryllium control and analog formulations as well as IMH-2 formulations. Approximately 37 IMH-2 and 90 beryllium motors will be evaluated under this task. The test motors shall contain a nominal 10- to 15-lb propellant charge and exhibit mass flow rates of approximately 5 lb/sec or greater. The task will be divided into two phases. In phase A, a formulation screening will be conducted, with the bulk of the motors to be fired at approximately 1000 psia exhausted to Bacchus ambient pressure (~ 12.2 psia) with optimum expansion ratio. Phase B will more extensively characterize selected high performance formulations. Table IV contains a breakdown of various areas to be investigated under Task II.

TABLE IV

TASK II, FORMULATION SCREENING

Subtask	Purpose	No. Firings (Be)	No. Firings (IMH-2)
Phase A			
II-6	Efficiency correlations with Be propellants	51	--
II-7	Oxidizer particle size studies with Be propellants	9	--
II-8	Optimum nozzle geometry	12	--
II-9	Increased L* studies	4	10
II-10	IMH-2/AP propellants	--	6
II-11	IMH-2/AN or HMX propellants	--	10
Phase B			
II-12	Characterization of selected Be and IMH-2 propellants	4	11

B.   LABORATORY FORMULATION AND PROCESSING STUDIES

1.   Beryllium Propellants

All laboratory formulation work was completed on the beryllium analog propellants during the second quarter. The pertinent data are summarized in Table V.

During this quarter, a problem was encountered with marginal processibility of the initial castings of VIN and VIJ (45 μ) formulations in the pilot plant. The processing problem with VIN was solved by removing 25 percent of the fines from the AN oxidizer. For VIJ, a heated mix cycle was partially successful in improving processibility.

2.   IMH-2 Propellants

Laboratory formulations and processing studies continued on the four IMH-2 propellants selected for characterization based on the Task I correlations. Table VI contains a summary of these propellants.

Previous work with conventional IMH-2 double-base propellants has shown that processibility becomes marginal at 15 percent IMH-2 loadings for most IMH-2 lots. As a result, posttreatment methods were investigated as a means to increase IMH-2 loadings. Of the various methods tried, wax coatings and recrystallization of AP/IMH-2 from an AP-saturated water dispersion showed the most promise. Additional details of these posttreatments are given in Report No. AFRPL-TR-66-11.

During this quarter, major emphasis was placed on three propellants, VJA, VIX, and VIY (with waxed and with AP-treated IMH-2). Laboratory work consisted of evaluating the processing characteristics of vacuum baked (posttreated) IMH-2 in the candidate formulations. The following IMH-2 treatments were evaluated:

(a) Ground and vacuum baked IMH-2

(b) Wax-coated IMH-2 (1 percent wax coatings)

(c) AP-treated IMH-2

Table VII shows a summary of data obtained from 300-gm mixes using various posttreatments. The first series of mixes shown, 69-65 through 60-69, used lots 95 and 95A in the FIQ formulation. The FIQ formulation is being used for motor evaluation under Contract AF 04(611)-10742 and is reported here to provide additional data on IMH-2 processing.

Propellants made with these lots were consistently porous when made with IMH-2 which had been vacuum baked 4 to 8 hr in addition to the 4-hr Ethyl bake. However, when the bake cycle was extended to 16 to 22 hr,

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TABLE V

BERYLLIUM PROPELLANTS FOR IMPULSE EFFICIENCY STUDIES

	Propellant Type										
	VIH	VII	VIJ	VIJ	VIJ	VIK	VIL	VIM	VIN	VIO	VIG
Formulation (wt %)											
NC (ENC, 10μ)	10.0	15.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
NQ	38.5	27.5	32.5	32.5	32.5	38.5	38.5	30.0	30.0	34.0	33.0
AP	32.5(45μ)	32.5(90μ)	37.5(45μ)	37.5(90μ)	37.5(180μ)	34.0(45μ)	18.0(45μ)	--	--	10.5(45μ)	8.0(90μ)
HMX (Class A)	--	--	--	--	--	--	--	37.5	39.0	33.0	--
AN (Hercules No. 3)	--	--	--	--	--	--	18.0	--	--	--	--
TAGNO3	--	--	--	--	--	--	--	--	--	--	31.5
Be (FP-17)	15.5	15.5	15.5	15.5	15.5	14.0	12.0	15.5	14.0	8.0	12.5
Res	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2-NDPA	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
TA	1.5	7.5	2.5	2.5	2.5	1.5	1.5	5.0	5.0	2.5	--
ADN	--	--	--	--	--	--	--	--	--	--	2.0
Theoretical											
Isp-100/14.7 (sec)	278.0	278.7	277.4	277.4	277.4	276.5	281.1	281.2	278.6	281.1	290.7
Tc (°K)	4173	3971	4145	4145	4145	4109	4408	3820	3744	3758	3633
ρ (gm/cc)	1.718	1.679	1.727	1.727	1.727	1.720	1.715	1.639	1.638	1.718	1.608
O.R.*	1.169	1.050	1.171	1.171	1.171	1.269	1.235	1.177	1.278	1.379	1.017
Sensitivity**											
Impact (cm/2kg)	11 (33)	11 (17)	3.5 (21)	3.5 (41)	6.9 (11)	3.5 (64)	3.5 (26)	3.5 (51)	11 (64)	3.5 (3.5)	3.5 (33)
Friction (lb @ ft/sec)	52 @ 8 (37 @ 8)	32 @ 6 (155 @ 8)	23 @ 6 (86 @ 8)	23 @ 8 (52 @ 8)	40 @ 6 (48 @ 8)	40 @ 8 (54 @ 8)	40 @ 8 (48 @ 8)	29 @ 8 (230 @ 8)	48 @ 8 (280 @ 8)	30 @ 8 (155 @ 8)	17 @ 5 (300 @ U)
Electrostatic discharge (joules)	>6.25 (>6.25)	>5.0 (>5.0)	0.250 (--)	>5.0 (>6.25)	0.250	>6.25 (1.25)	>6.25 (>6.25)	>6.25 (>6.25)	>6.25 (>6.25)	0.25 (0.25)	0.25 (>5.0)
Autoignition (°C)	204 (208)	231 (199)	212 (201)	214 (193)	218 (201)	200 (198)	207 (189)	200 (223)	204 (223)	213 (213)	214 (210)
Differential thermal analysis, ignition (°C)	172 (170)	174 (174)	162 (170)	173 (171)	176 (163)	170 (173)	173 (172)	170 (173)	175 (175)	166 (172)	162 (149)
Physical properties											
Tensile (psi)	103	96	--	98	--	96	66	59	88	--	125
Elongation (%)	32	34	--	23	--	30	43	22	22	--	20
Modulus (psi)	304	377	--	526	--	398	280	340	425	--	1000
Burning rates***											
r @ 1000 psia	0.97	0.50	0.98	0.75***	0.55	1.02	0.07	--	0.33	0.68	0.50
Exponent	0.49	0.39	--	0.47***	--	0.39	0.38	--	--	0.76	0.57

*Oxidation ratio

**First number is for uncured propellant, number in parenthesis is for cured propellant

***Motor data

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TABLE VI

LMH-2 FORMULATIONS

	Propellant Type			
	VIX	VIY	VIZ	VJA
Formulation (wt %)				
NC	10.0	10.0	10.0	10.0
NG	50.0	50.0	50.0	50.0
AP	23.0	21.0	19.0	--
HMX	--	--	--	24.0
LMH-2	15.0	17.0	19.0	15.0
Res	1.0	1.0	1.0	--
2-NDPA	1.0	1.0	1.0	1.0
Theoretical				
I_{sp} (1000/14.7)(sec)	303.7	308.9	313.8	309.3
Tc (°K)	3678	3679	3672	3621
ρ (gm/cc)	1.356	1.319	1.284	1.355
Oxidation ratio	1.342	1.219	1.113	1.146

nonporous grains were obtained. When mixes 94-58, 94-59, and 94-65 were made
with lot 96 baked 4 to 8 hr, they were also porous. Mix 94-67 used lot 96
with an 8-hr bake cycle prior to wax treatment and was nonporous. It should
be noted that in effect the wax treatment provides an extended bake cycle
with the volatile wax solvent being stripped off under full vacuum for 16
hr at 70° C. Based on the above results, it appeared that extended baking
cycles would be necessary to eliminate porosity for propellants made without
AP-treated or wax-treated LMH-2 (for some LMH-2 lots).

Additional mixes of the FIQ formulation were made with the extended
baked lot 95A and with the VIX and VJA formulations using extended baked
lots 96 and 97. The resulting grains were nonporous. The VIY formulation
was also successfully made using AP- and wax-treated lot 96. The LMH-2
was baked 8 hr prior to AP treating. Extended baking cycles and wax treating
were also applied to lot 93 with the VJA formulation. The resulting grains
were porous, however, and this anomalous lot is still under investigation.

Two additional posttreatments were also investigated. In the
first treatment, lot 95A was water washed overnight at 25° C. The resulting
material gave a nonporous grain (mix 94-36). The second method consisted of
an acetonitrile-HMX wash. The resulting material was incorporated in the
VIX formulation (mix 94-78) and gave a porous grain.

Because of its simplicity and success, the extended baking cycle
will be used on all LMH-2 lots without AP or wax treatment. For the wax- and

TABLE VII

LMH-2 PROCESS STUDIES

Mix No.	Prop Type*	Mix Size (gm)	LMH-2 Lot No.	Special Treatment	Mix Temp (°F)	Viscosity @ 3 rpm	Cure Conditions (days/°F/psia)	Comments
69-65	FIQ-S(2)	500	95	4 hr @ 100° C	80	24,000	6/120/30	Slightly porous
69-77	FIQ-S(2)	300	95	18 hr @ 100° C	86	14,500	6/120/30	Nonporous
69-64	FIQ-S(1)	500	95A	4 hr @ 100° C	80	60,000	6/120/30	Porous
60-69	FIQ-S(1)	300	95A	7-1/2 hr @ 80° C	76	16,000	6/120/30	Slightly porous
69-78	FIQ-S(1)	300	95A	22 hr @ 100° C	80	16,500	6/120/30	Nonporous
BC-94-86	FIQ-S(1)	300	95A	Water washed	70	18,648	--	Nonporous
BC-95-1	FIQ-S(1)	300	95A	16 hr @ 100° C	70	18,648	5/120/30	Slightly porous**
BC-95-6	FIQ-S(1)	300	95A	16 hr @ 100° C	72	13,320	--	Nonporous
BC-95-7	FIQ-S(2)	300	95	16 hr @ 100° C	78	10,323	--	Nonporous

* Propellant type:

Ingredent (%)	FIQ-S(1)	FIQ-S(2)
NC	10.0	10.0
NG	45.0	45.0
TA	5.0	5.0
LMH-2	12.0 (ground)	12.0 (unground)
AP	17.3 (200μ)	17.3 (200μ)
AP	8.7 (45μ)	8.7 (45μ)
2-NDPA	1.0	1.0
Res	1.0	1.0

** Deaerated at 40 mm Hg after mixing; may be some deaeration voids

TABLE VII (Cont)

LMH-2 PROCESS STUDIES

Mix No.	Prop Type	Mix Size (gm)	LMH-2 Lot No.	Special Treatment	Mix Temp (°F)	Viscosity @ 3 rpm	Cure Conditions (days/°F/psia)	Comments
94-57	VIY	300	93-1	4 hr @ 100° C, AP treated	78	180,000	5/120/30	Nonporous
94-67	VIY	500	96	7-1/2 hr @ 80°C, waxed	98	93,000	5/120/30	Nonporous
BC-95-3	VIY	500	96	8 hr @ 100° C, AP treated	105	31,968	5/120/30	Nonporous
94-58	VIX	500	96	4 hr @ 100° C	64	140,000	5/120/0	Fine porosity
94-65	VIX	300	96	8 hr @ 80° C	98	45,000	5/120/30	Porous
94-94	VIX	300	96	16 hr @ 100° C	104	56,440	5/120/30	Nonporous
BC-95-21	VIX	500	97	16 hr @ 100° C	100	64,740	5/120/30	Nonporous
BC-95-24	VIX	500	97	16 hr @ 100° C, waxed	104	42,624	5/120/30	Nonporous
94-56	VJA	300	95A	None	68	32,600	5/120/30	Porous
94-59	VJA	500	96	4 hr @ 100° C	62	61,420	5/120/30	Porous
94-78	VJA	300	96	HMX treated	98	41,958	5/120/30	Porous
95-2	VJA	500	96	16 hr @ 100° C	102	35,298	5/120/30	Nonporous
95-20	VJA	300	93	16 hr @ 100° C	102	250,000	5/120/30	Porous
95-22	VJA	500	97	16 hr @ 100° C	100	68,000	5/120/30	Nonporous
95-23	VJA	500	93	16 hr @ 100° C, waxed	100	44,820	5/120/30	Porous

AP-treated material, an 8- to 16-hr baking cycle, coupled with the usual 16- to 20-hr solvent stripping, will be used.

From processing considerations, castability is felt to be marginal at viscosities above 140,000 cps because of the thixiotropic nature of the propellants. As shown in Table VII all lots received to date, with the exception of lot 93, can be processed using a heated mix cycle coupled with the wax or AP treatments in VIX, VIY, and VJA formulations. The high viscosity of lot 93 precludes its use in the higher viscosity propellant VIY.

A secondary study was also conducted during the report period on the desorption of gas by LMH-2 under vacuum. This study was initiated because of the large volume increase experienced with FIQ propellants during the pot deaeration vacuum cycle. Volume increases of as much as 400 percent were observed.

This large volume increase presents a problem with the present pilot-plant mixer with a free-board limited to approximately 150 percent. It was also felt that the pre-cure gassing might be related to the porous grain problem. As a consequence, a series of tests were run in which various LMH-2 lots were exposed to solvent under vacuum conditions. Results of these tests are summarized in Table VIII. The test method consisted of placing 50 gm of pre-evacuated solvent and 12 gm of LMH-2 in a slurry in a vacuum bell jar. Vacuum was then applied and the volume increase observed visually.

In Run No. 1 (Table VIII) a full vacuum of 4 mm Hg was applied for a period of 40 min to lots 95A and 96 with various posttreatments. A significant volume increase occurred with all samples tested which were exposed to NG solvent. The water-washed lot 95A showed a volume increase of 400 percent, whereas the wax and AP treated material both showed approximately 100 percent increases. Lots 95A and 96, with extended baking cycles, showed volume increases intermediate to these extremes. Visual observation of these tests indicated the volume change was the result of gas liberation coupled with a thick (high surface tension) film of LMH-2 trapping the gas during expansion. Estimates of the volume of gas liberated were made from the volume increases, but could be considerably lower than the actual amount because of gas loss through the film. It was also noted in Run No. 1 that LMH-2 exposed to TA showed no gas evolution.

Because of the apparent solvent differences, a compatibility problem between LMH-2 and NG was indicated. Micro tests were conducted to collect and analyze the off gases by gas chromatography. The resulting analysis showed only air was liberated.

Two additional runs were made (Table VIII) in which the vacuum was incrementally decreased beginning at 40 mm Hg to see if the amount of air liberated was pressure dependent. None of the materials tested, with the exception of the two "as received" lots, showed any desorption above

TABLE VIII

FOAMING STUDIES

Run No.	Material	LMH-2 Lot	Special Treatment	Vacuum (mm Hg)	Time (min)	Volume Change (%)	Volume Liberated (STP/100 gm)
1	NG + LMH-2	96	AP treated	4	40	100	2.1
	NG + LMH-2	96	Waxed	4	40	100	2.1
	NG + LMH-2	96	16 hr vacuum bake	4	40	200	4.2
	NG + LMH-2	95A	Water washed	4	40	400	8.4
	TA + LMH-2	95A	Water washed	4	40	None	0
	NG + LMH-2	95A	12 hr vacuum bake	4	40	125	2.5
	NG + LMH-2	95A	16 hr vacuum bake	4	40	175	3.5
2	NG + LMH-2	96	AP treated	40	40	None	0
	NG + LMH-2	96	Waxed	40	40	None	0
	NG + LMH-2	96	16 hr vacuum bake	40	40	None	0
	NG + LMH-2	96	AP treated	20	2C	25	2.1
	NG + LMH-2	96	Waxed	20	20	None	0
	NG + LMH-2	96	16 hr vacuum bake	20	20	None	0
	NG + LMH-2	96	AP treated	10	20	40	2.1
	NG + LMH-2	96	Waxed	10	20	None	0
	NG + LMH-2	96	16 hr vacuum bake	10	20	40	2.1
	NG + LMH-2	96	AP treated	4	20	50	1.1
	NG + LMH-2	96	Waxed	4	20	50	1.1
	NG + LMH-2	96	16 hr vacuum bake	4	20	150	3.3
3	NG + LMH-2	95A	None	40	40	25	0.8
	NG + LMH-2	96	None	40	40	25	0.8
	NG + LMH-2	95A	None	4	20	75	1.5
	NG + LMH-2	96	None	4	20	100	2.0

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20 mm Hg. Possibly, because of the nature of the test, the amount of gas
desorbed with a given material was only partially pressure dependent.

Only limited conclusions can be made from the above tests; how-
ever, it has been shown that significant amounts of adsorbed air were
liberated from IMH-2 under certain conditions. The data in Table VIII show
that between 1 and 8 cc of gas per 100 gm IMH-2 at standard conditions were
liberated, depending on the various IMH-2 lot or posttreatment. To obtain
more quantitative results, the Ethyl Corporation was contacted and recently
reported approximately 11 cc of air were desorbed from lot 95A under vacuum
at room temperature.* To determine the effect of not removing the adsorbed
air on cured propellant, FIQ mixes were made at both Bacchus and ABL with
evacuation cycles at 40 mm Hg. The ABL mix was made entirely under vacuum.
The Bacchus mix was poc deaerated only prior to casting. The ABL mix was
nonporous, and the Bacchus mix showed slight porosity (mix 95-1), which
could have resulted from a larger amount of air entrapped during mixing.
Both mixes used lot 95A baked for 16 hr. Based on the results to date, it
is questionable whether the porous grain problem is related directly to
desorbed air. Additional quantitative work is recommended to determine the
amount of adsorbed air present between lots and with various posttreatments.
The initial castings of FIQ and VIY will be made using a 40 mm Hg mix and
cast cycle.

C.   BALLISTIC TESTING

    1.   Castings

        a.   Beryllium

            A total of 34 beryllium 15PC motors were cast during this
report period. A summary of the castings and firings is presented in
Table IX. All grains were X-rayed and 30 were found to be acceptable for
firing. Minor processing problems were observed in manufacturing VIJ
(45 μAP) and VIN compositions. Due to thick, highly viscous mixes the
compositions were difficult to cast and incorporate. One grain of each
composition was found to be discrepant because of poor propellant consoli-
dation resulting from the marginal processibility. Later mixes of the VIN
formulation were successfully processed with 25 percent of the fines screened
out of the oxidizer. The VIJ (45 μAP) mixes were heated during the mix
cycle to reduce the viscosity.

        b.   IMH-2

            Six IMH-2 15PC motors of the VIY formulation were success-
fully cast during this report period. Three of the grains contained AP-
treated IMH-2, and three contained wax-treated IMH-2. All castings were
made with lot 96 IMH-2. All grains were X-rayed and found acceptable for
firing.

* Personal communication with Dr. Fred Frey of the Ethyl Corporation

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TABLE IX

SUMMARY OF CASTINGS AND FIRINGS

Purpose	Propellant Type	Grain Type	No. Castings*	No. Firings*	Firings**
Beryllium efficiency studies	VCP	Standard		2	3
		Mod-1		1	3
	VIG	Standard	3	3	3
	VIH (45μ AP)	Standard			3
	VII	Mod-1	3	3	3
		Mod-2	3	3	3
	VIJ (90μ AP)	Standard		1	3
		Mod-1		1	3
	VIK	Standard		2	3
		Mod-1		3	3
	VIL	Standard		3	3
		Mod-1		2	2
		Mod-2		1	1
	VIN	Mod-2	4	3	3
	VIO	Mod-1	3	3	3
Oxidizer particle size with beryllium propellants	VIJ (45μAP)	Mod-1	4	2	2
	(180μAP)	Standard	3	3	3
	(90μAP)	Standard	3	3	3
Optimum nozzle geometry with Be	VCP	Standard		4	4
	VIJ (90μAP)	Standard	2	7	7
Increased I* studies	VCP	Standard	2	1	1
	VIY (wax-coated IMH-2)	Standard	3	1	1
	VIY (AP-treated IMH-2)	Standard	3	1	1
Characterization of select propellants	VCP	Standard	2		
		Mod-1	2		
Total			40	53	64

*This report period
**To date

2. __Firings__

    a. __Beryllium__

        A total of 51 beryllium 15 PC motor firings were made during this report period. A summary of the firings is presented in Table IX. A complete ballistic summary of individual firings are contained in Tables X through XIII. These firings complete all but the VIN and data confirmation firings under the beryllium efficiency studies and complete the nozzle approach and AP particle size studies. Only limited testing has been completed on the high L* studies.

        All firings except one were successful. One VLJ firing (IM 2-18) with a 15 degree nozzle approach cone suffered a burnthrough in the forward end of the motor. The burnthrough resulted from leakage in a pressure takeoff fitting, which allowed the chamber gasses to escape the forward end of the motor. The resulting burnthrough left a hole about 2 in. in diameter in the motor.

        A problem with poor efficiency resulting in apparent unstable burning occurred with the VIN firings. Figure 9 shows p-K-r data based on three VIN firings. As noted, an apparent slope change occurred in the p-r and p-K curves above 430 psia. This anomalous behavior is also apparent in the pressure-time curves for the firings shown in Figure 10 and the change in the discharge coefficients from 0.0078 sec^{-1} for the low pressure firings to 0.0064 sec^{-1} for the high pressure firing. One additional VIN firing will be made to explore this anomaly further.

        Firings made for optimum nozzle studies were observed to have greater nozzle erosion as the approach angle was reduced. Also VLJ firings were observed to have greater nozzle erosion than VCP. The results are shown in Figure 11.

    b. __IMH-2__

        Two firings of VIY were successfully completed in the high L* studies. One firing each of VIY containing waxed IMH-2 and AP-treated IMH-2 was made. Table XIII shows the ballistic data obtained from these firings. Figure 12 shows the pressure-time curve for the VIY (waxed) firing. Both firings were made at low L* values of 110 to 130. As shown, the wax-treated material gave a delivered impulse, Isp^{15}_{1000}, of 278.6 sec for an efficiency of 90.2 percent. The AP-treated material gave an efficiency of 1 percent lower. This lower efficiency was consistent with the trend obtained by combustion bomb firings as reported in Report No. AFRPL-TR-66-11. Duplicate firings of those previously described plus six firings at high L* values will be made. In addition, two VCP and two VII firings will be made to complete the L* studies.

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TABLE X

BERYLLIUM EFFICIENCY STUDIES

Propellant type	VCP	VCP	VCP	VCP	VCP	VCP	VIII	VIII	VIII	VII	VII	VII	VII	VII
Motor design	15PC-1	15PC-1	15PC-1	15PC	15PC	15PC	15PC	15PC		15PC-2	15PC-2	15PC-2	15PC-1	15PC-1
Grain No.	882B	S87B	S139B	S86B	S76B	S75B	S89B	S81B	S78B	S129B	S130B	S131B	S132B	S133B
Firing No.	LM2-1	LM2-6	LM2-55	LM2-16	LM2-25	LM2-7	LM2-3	LM2-8	LM2-9	LM2-36	LM2-47	LM2-48	LM2-39	LM2-49
Propellant wt (lb)	14.88	14.92	14.91	15.21	15.17	15.12	15.11	15.24	15.04	14.84	14.82	14.66	14.71	14.73
Powder wt (lb)	0.04	0.05	0.04	0.06	0.05	0.05	0.05	0.05	0.06	0.06	0.07	0.06	0.05	0.06
K (S/A_t)	104.0	103.3	104.0	142.5	142.5	143.2	139.8	110.5	109.2	111.1	138.1	139.0	204.9	182.2
t_a (sec)	1.884	1.874	2.237	1.900	1.804	1.817	1.148	1.322	1.350	2.49	2.218	2.228	2.205	2.409
t_b (sec)	1.794	1.770	2.117	1.756	1.708	1.715	1.043	1.274	1.280	2.36	2.021	2.080	2.061	2.264
$\bar{P}_a$ (psia)	578	586	489	1043	1069	1074	1604	1121	1085	337	460	454	903	751
$\bar{P}_b$ (psia)	592	600	502	1085	1098	1103	1695	1144	1118	348	484	472	935	775
Pmax (psia)	657	650	545	1159	1160	1175	1885	1223	1202	399	544	527	1066	881
Pamb (psia)	12.41	12.12	12.29	11.94	11.85	12.10	12.41	10.20	12.19	12.17	12.22	12.307	8.141	12.15
$\bar{r}$ (in./sec)	0.557	0.565	0.477	0.751	0.773	0.764	1.246	1.028	1.023	0.317	0.371	0.373	0.490	0.446
$\dot{m}$ (lb/sec)	7.90	7.96	6.67	8.01	8.41	8.32	13.16	11.53	11.14	5.96	6.68	6.58	6.67	6.12
C_d (sec^{-1})	0.00580	0.00578	0.00583	0.00576	0.00587	0.00581	0.00613	0.00604	0.00603	0.00600	0.00614	0.00614	0.00623	0.00611
ε (A_e/A_t)	5.615	5.616	5.717	9.640	9.590	9.607	9.576	9.624	9.607	5.627	5.623	5.604	9.477	9.625
$\bar{F}_a$ (lb$_f$)	1939	1995	1622	2112	2227	2209	3570	3088	2949	1350	1586	1554	1757	1530
Isp del $\left(\dfrac{\text{lb}_f \cdot \text{sec}}{\text{lbm}}\right)$	245.6	250.7	244.5	263.9	265.1	265.5	272.1	267.4	264.0	226.7	237.6	236.2	263.7	250.3
Theoretical Isp at firing conditions	266.7	269.5	265.0	287.9	288.5	288.2	289.6	286.8	283.4	250.4	259.9	259.1	287.3	275.5
Efficiency	91.40	93.02	92.26	91.66	91.89	92.1	93.96	93.48	93.44	90.54	91.42	91.16	91.79	90.86
$\dfrac{15}{\text{Isp } 1000}$	258.7	263.2	261.1	259.4	260.1	260.6	261.2	259.9	259.8	232.3	254.8	234.1	235.8	253.2
Isp del (c)*	245.0	250.0	243.9	263.1	264.4	264.9	271.4	267.4	264.0	225.9	236.6	235.4	262.7	249.5
Efficiency (c)*	91.18	92.76	92.04	91.39	91.65	91.92	93.71	93.24	93.16	90.22	91.04	90.85	91.44	90.56
Isp $\dfrac{15}{1000}$ (c)*	258.0	252.5	260.5	258.6	259.4	260.1	260.5	259.2	259.0	251.4	253.7	253.2	254.6	252.4

Note: Refer to end of table for footnotes

TABLE X (Cont)

BERYLLIUM EFFICIENCY STUDIES

Propellant type	VII	VIJ	VIJ	VIJ	VIJ	VIJ	VIJ	VIK	VIK	VIK	VIK	VIK	VIK	VIL
Motor design	15PC-1	15PC-1	15PC-1	15PC-1	15PC	15PC	15PC	15PC-1	15PC-1	15PC-1	15PC	15PC	15PC	15PC-1
Grain No.	S134B	S04B	S94B	S85B	S91B	S92B	S97B	S88B	S89B	S90B	S72B	S105B	S114B	S116B
Firing No.	LH2-50	LH2-2**	LH2-12	LH2-13	LH2-4	LH2-5	LH2-11**	LH2-14	LH2-27	LH2-28	LH2-10	LH2-15	LH2-29	LH2-26
Propellant wt (lb)	14.38	14.95	15.12	15.01	15.20	15.24	15.00	15.03	14.95	14.94	14.92	14.74	15.30	15.03
Powder wt (lb)	0.04	0.06	0.04	0.05	0.04	0.03	0.05	0.05	0.05	0.04	0.05	0.04	0.05	0.06
K (S/A_t)	209.3	101.8	102.9	102.5	140.5	141.3	128.6	77.00	70.2	70.8	109.6	96.5	98.1	95.8
t_a (sec)	1.809	1.824	1.820	1.831	1.594	1.830	1.927	1.238	1.332	1.436	1.227	1.459	1.425	1.460
t_b-sec	1.713	1.686	1.697	1.720	1.593	1.721	1.875	1.164	1.246	1.368	1.165	1.413	1.357	1.363
$\bar{P}_a$ (psia)	1135	566	576	568	1103	1019	892	621	534	491	1182	879	923	680
$\bar{P}_b$ (psia)	1167	595	597	587	1141	1054	907	640	552	503	1216	895	950	703
Pmax (psia)	1291	671	647	639	1245	1145	999	696	595	537	1303	959	1022	762
$\bar{P}$amb (psia)	12.303	12.41	11.97	11.92	12.11	12.10	12.00	12.09	12.18	12.14	12.08	11.44	10.33	11.54
$\bar{r}$ (in./sec)	0.590	0.593	0.589	0.581	0.822	0.761	0.693	0.859	0.797	0.731	1.116	0.927	0.965	0.737
$\dot{m}$ (lb/sec)	7.95	8.20	8.31	8.20	8.97	8.33	7.78	12.14	11.22	10.40	12.81	10.10	10.74	10.29
c_d (sec^{-1})	0.00603	0.00611	0.00611	0.00614	0.00608	0.00612	0.00610	0.00619	0.00606	0.00614	0.00606	0.00606	0.00606	0.00597
ϵ (A_e/A_t)	9.742	5.591	5.616	5.644	9.595	9.609	9.022	5.555	5.489	5.631	9.653	9.478	9.425	5.528
$\bar{F}_a$ (lb$_f$)	2032	1979	2031	1996	2367	2180	1991	3000	2725	2495	3221	2638	2839	2605
Isp del $\left(\dfrac{\text{lb}_f\text{-sec}}{\text{lbm}}\right)$	262.1	244.2	244.6	243.7	263.9	261.9	255.8	247.3	243.1	240.0	265.1	261.5	264.8	253.3
Theoretical Isp at firing conditions	284.6	262.9	264.1	263.9	283.1	281.6	280.6	264.6	261.1	259.4	283.7	278.5	279.8	271.9
Efficiency	92.09	92.89	92.62	92.35	93.22	93.00	91.17	93.46	93.11	92.52	93.44	93.90	94.64	93.16
Isp $^{15}_{1000}$	256.7	257.7	256.9	256.2	258.6	258.0	252.9	258.4	257.5	255.8	258.4	259.6	261.7	261.5
Isp del (c)*	261.5	243.4	244.1	243.0	263.4	261.5	255.1	246.6	242.4	239.5	264.4	260.9	263.8	252.5
Efficiency (c)*	91.88	92.58	92.43	92.08	93.04	92.86	90.91	93.20	92.84	92.33	93.20	93.68	94.28	92.87
Isp $^{15}_{1000}$ (c)*	256.1	256.6	256.4	255.4	258.1	257.6	252.2	257.7	256.7	255.3	257.7	259.0	260.7	261.1

Note: Refer to end of table for footnotes

TABLE X (Cont)

BERYLLIUM EFFICIENCY STUDIES

Propellant type	VIL	VIL	VIL	VIL	VIL	VIN****	VIN	VIN	VIO	VIO	VIO	VIG	VIG	VIG
Motor design	15PC-2	15PC-1	15PC	15PC	15PC	15PC-2	15PC-2	15PC-2	15PC-1	15PC-1	15PC-1	15PC-1	15PC-1	15PC-1
Grain No.	S109B	S117B	S110B	S111B	S115B	S112B	S144B	S142B	S120B	S121B	S122	S135B	S136B	S137B
Firing No.	LM2-40	LM2-41	LM2-42	LM2-43	LM2-44	LM2-30	LM2-58	LM2-56	LM2-31	LM2-51	LM2-52	LM2-38	LM2-45	LM2-46
Propellant wt (lb)	15.14	14.96	15.13	15.15	15.24	14.66	14.00	14.12	15.07	14.93	15.00	14.09	14.11	14.12
Powder wt (lb)	0.06	0.04	0.06	0.04	0.03	0.06	0.06	0.06	0.05	0.05	0.05	0.04	0.04	0.04
$K\ (S/A_t)$	86.6	81.4	114.8	115.0	115.5	245.0	308.3	414.0	162.4	119.6	119.8	179.7	207.1	206.0
t_a (sec)	1.261	1.648	1.578	1.565	1.582	4.931	4.203	1.900	1.163	1.725	1.866	2.310	2.032	2.097
t_b-sec	1.109	1.536	1.509	1.507	1.522	4.184	3.885	1.734	1.071	1.636	1.767	2.192	1.953	1.966
$\bar{P}_a$ (psia)	538	526	983	998	992	296	398	1482	1472	749	698	772	969	936
$\bar{P}_b$ (psia)	569	545	1008	1020	1013	324	421	1567	1532	778	717	794	990	1010
$\bar{P}_{max}$ (psia)	611	585	1077	1124	1097	406	576	1817	1639	873	801	848	1096	1052
$\bar{P}_{amb}$ (psia)	12.16	12.18	12.16	12.34	12.13	12.27	12.35	12.28	12.14	12.214	12.177	12.26	12.21	12.21
$\bar{r}$ (in./sec)	0.680	0.657	0.875	0.876	0.861	0.182	0.193	0.421	0.943	0.618	0.574	0.456	0.512	0.509
$\dot{m}$ (lb/sec)	12.01	9.08	9.59	9.68	9.63	2.97	3.33	7.43	12.96	8.66	8.04	6.10	7.22	7.18
C_d (sec^{-1})	0.00591	0.00596	0.00598	0.00594	0.00593	0.00752	0.00785	0.00638	0.00586	0.00569	0.00572	0.00582	0.00609	0.00609
$\epsilon\ (A_e/A_t)$	5.609	5.568	9.546	9.565	9.493	9.648	9.633	6.631	9.621	9.476	9.463	9.507	9.552	9.400
$\bar{F}_a$ (lb$_f$)	3008	2237	2523	2569	2548	557	710	1903	3516	2223	2038	1562	1810	1740
Isp del $\left(\dfrac{lb_f\text{-sec}}{lbm}\right)$	250.8	246.7	263.6	263.5	264.7	200.8	213.1	256.6	271.9	258.3	254.7	256.3	260.9	258.5
Theoretical Isp at firing conditions	268.1	265.7	284.5	284.6	284.7	235.3	252.4	282.4	291.9	277.8	275.9	288.0	293.5	292.8
Efficiency	93.55	92.85	92.65	92.59	92.98	85.3	84.43	90.86	93.15	92.98	92.32	88.99	88.89	89.29
Isp_{1000}	263.0	261.0	260.4	260.3	261.4	238.9	236.5	254.4	261.9	261.4	259.5	258.7	258.4	256.7
Isp del (c)*	250.0	246.2	262.8	263.0	264.3	200.0	212.2	255.7	271.1	257.4	254.1	255.8	260.3	257.9
Efficiency (c)*	93.25	92.66	92.37	92.41	92.83	85.00	84.07	90.55	92.87	92.73	92.10	88.82	88.69	88.08
Isp_{1000} (c)*	262.1	260.5	239.7	259.8	261.0	238.1	235.5	253.6	261.1	260.7	258.9	258.2	257.8	256.0

Notes: All efficiency values were calculated at the actual firing conditions.
Isp_{1000} and Isp_{1000} (c) values were calculated by multiplying efficiency times the theoretical Isp at standard conditions

* Values corrected for powder embedment
** 4 second hangfire
*** Poor thrust-time trace data is questionable
**** All impulse data questionable because of possible flow separation

TABLE XI

NOZZLE APPROACH STUDY

Propellant type	V3P	VCP	VCP	VCP	V1J	V1J	V1J	V1J	V1J	V1J
Motor Design	15PC	15PC	15PC	15PC	15PC	15PC	15PC	15PC	15PC	15PC
Grain No.	896B	S100B	S101B	S119B	S93B	S98B	S99B	S108B	S140B	S141B
Firing No.	LH2-19*	LH2-24*	LH2-22**	LH2-37**	LH2-17*	LH2-21*	LH2-23*	LH2-20**	LH2-53**	LH2-54
Propellant wt (lb)	15.15	15.09	15.25	15.25	15.14	15.22	15.10	15.36	15.23	15.33
Powder wt (lb)	0.05	0.03	0.05	0.05	0.04	0.05	0.04	0.04	0.05	0.03
K (S/A_t)	141.3	140.0	140.2	139.9	139.3	137.7	136.2	141.3	142.4	142.8
t_a (sec)	1.953	1.975	1.837	1.890	1.815	1.903	1.961	1.833	1.760	1.784
t_b (sec)	1.850	1.881	1.745	1.817	1.646	1.822	1.859	1.737	1.690	1.695
$\bar{P}_a$ (psia)	974	957	1057	1046	1022	962	939	1044	1050	1055
$\bar{P}_b$ (psia)	1001	979	1089	1068	1053	984	968	1074	1074	1088
Pmax (psia)	1054	1019	1153	1146	1138	1080	1060	1173	1198	1388
Pamb (psia)	11.69	11.64	11.43	12.26	11.93	7.29	11.59	7.61	12.26	12.32
$\bar{r}$ (in./sec)	0.706	0.702	0.756	0.721	0.796	0.719	0.705	0.754	0.775	0.779
$\dot{m}$ (lb/sec)	7.76	7.64	8.30	8.07	8.34	8.00	7.70	8.38	8.65	8.59
C_d (sec^{-1})	0.00595	0.00592	0.00583	0.00568	0.00611	0.00612	0.00604	0.00600	0.00611	0.00513
ε (A_e/A_t)	9.626	9.599	9.555	9.507	9.613	9.411	9.551	9.544	9.451	9.414
P_a (lb$_f$)	2056	2022	2204	2162	2200	2168	2029	2278	2261	2268
Isp del $\left(\dfrac{\mathrm{lb_f\text{-}sec}}{\mathrm{lbm}}\right)$	265.2	265.0	265.7	267.8	264.0	271.5	263.7	272.2	261.6	264.2
Theoretical Isp at firing conditions	286.9	286.6	288.9	287.3	281.9	288.0	280.6	288.8	281.7	281.8
Efficiency	92.44	92.46	91.97	93.21	93.65	94.27	93.98	94.25	92.87	93.75
Isp 15/1000	261.6	261.7	260.3	263.8	259.8	261.5	260.7	261.5	257.6	260.1
Isp del (c)*	264.6	264.6	265.0	267.2	263.5	270.8	263.2	271.7	260.9	263.8
Efficiency (C)*	92.23	92.32	91.72	93.00	93.47	94.03	93.80	94.08	92.62	93.61
Isp 15/1000 (c)*	261.0	261.3	259.6	263.2	259.3	260.8	260.2	261.0	256.9	259.7

Notes: *5° Approach
**15° Approach
Firing LH2-18 suffered a case burnthrough and all data was lost.
All efficiency values were calculated at the actual firing conditions.
Isp 15/1000 and Isp 15/1000 (c) values were calculated by multiplying efficiency times the theoretical Isp at standard conditions.

TABLE XII

AP PARTICLE SIZE STUDY

Propellant type	VIJ-5021	VIJ-5021	VIJ-5021	VIJ-5061	VIJ-5061
Motor Design	15PC-1	15PC-1	15PC-1	15PC	15PC
Grain No.	S123B	S124B	S125B	S126B	S128B
Firing No.	IM2-32	IM2-33	IM2-34	IM2-35	IM2-59
Propellant wt (lb)	15.10	15.07	15.16	15.36	14.27
Powder wt (lb)	0.05	0.05	0.05	0.04	0.05
K (S/A_t)	167.2	179.7	181.5	97.3	109.4
t_a (sec)	2.343	2.053	2.305	1.717	1.427
t_b (sec)	2.224	1.902	2.305	1.649	1.314
$\bar{P}_a$ (psia)	736	896	785	756	968
$\bar{P}_b$ (psia)	757	932	811	774	1014
$\bar{P}max$ (psia)	846	1065	911	838	1117
$\bar{P}amb$ (psia)	12.22	12.27	12.27	12.16	12.32
$\bar{r}$ (in./sec)	0.450	0.531	0.465	0.800	0.997
$\dot{m}$ (lb/sec)	6.45	7.34	6.58	8.95	10.0
C_d (sec^{-1})	0.00602	0.00607	0.00620	0.00609	0.00605
ϵ (A_e/A_t)	9.573	9.527	9.555	9.243	9.520
$\bar{F}_a$ (lb$_f$)	1637	1892	1659	2279	2637
Isp del $\left(\frac{lb_f\text{-sec}}{lbm}\right)$	254.2	257.9	252.1	255.0	264.0
Theoretical Isp at firing conditions	273.2	278.3	275.0	274.2	281.0
Efficiency	92.98	92.67	91.67	93.00	93.95
Isp $\frac{15}{1000}$	257.9	257.1	254.3	258.0	260.6
Isp del (c)*	253.5	257.2	251.4	254.4	263.3
Efficiency (c)*	92.72	92.42	91.42	92.78	93.70
Isp $\frac{15}{1000}$ (c)*	257.2	256.8	253.6	257.4	259.9

Notes: VIJ-5021 contains 180μ AP, VIJ-5061 contains 45μ AP
All efficiency values were calculated at the actual firing conditions.
Isp$\frac{15}{1000}$ and Isp $\frac{15}{1000}$ (c) values were calculated by multiplying efficiency times the theoretical Isp at standard conditions.
*Values corrected for powder embedment

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TABLE XIII

HIGH L* STUDY

Propellant type	VIY*	VIY**
Motor Design	15PC	15PC
Grain No.	S150BH	S152BH
Firing No.	LM2-60	LM2-61
Propellant wt (lb)	11.34	11.79
Powder wt (lb)	0.05	0.05
K (S/A_t)	100.2	127.3
t_a (sec)	1.690	1.199
t_b (sec)	1.592	1.106
$\bar{P}_a$ (psia)	671	1192
$\bar{P}_b$ (psia)	695	1245
$\bar{P}$max (psia)	749	1355
$\bar{P}$amb (psia)	12.27	12.29
$\bar{r}$ (in./sec)	0.823	1.166
$\dot{m}$ (lb/sec)	6.71	9.83
C_d (sec $^{-1}$)	0.00530	0.00556
ϵ (A_e/A_t)	7.446	9.663
$\bar{F}_a$ (lb_f)	1322	2778
Isp del $\left(\dfrac{lb_f\text{-sec}}{lbm} \right)$	271.5	283.2
Theoretical Isp at firing conditions	300.0	316.6
Efficiency	90.50	89.45
Isp $\frac{15}{1000}$	279.6	276.3
Isp del (c)***	270.6	282.3
Efficiency (c)***	90.20	89.16
Isp $\frac{15}{1000}$ (c)***	278.6	275.4

Notes: * Wax treated
    ** AP treated
    *** Values corrected for powder embedment
    All efficiency values were calculated at the actual firing conditions.
    $Isp\frac{15}{1000}$ and $Isp\frac{15}{1000}$ (c) values were calculated by multiplying efficiency times the theoretical Isp at standard conditions.
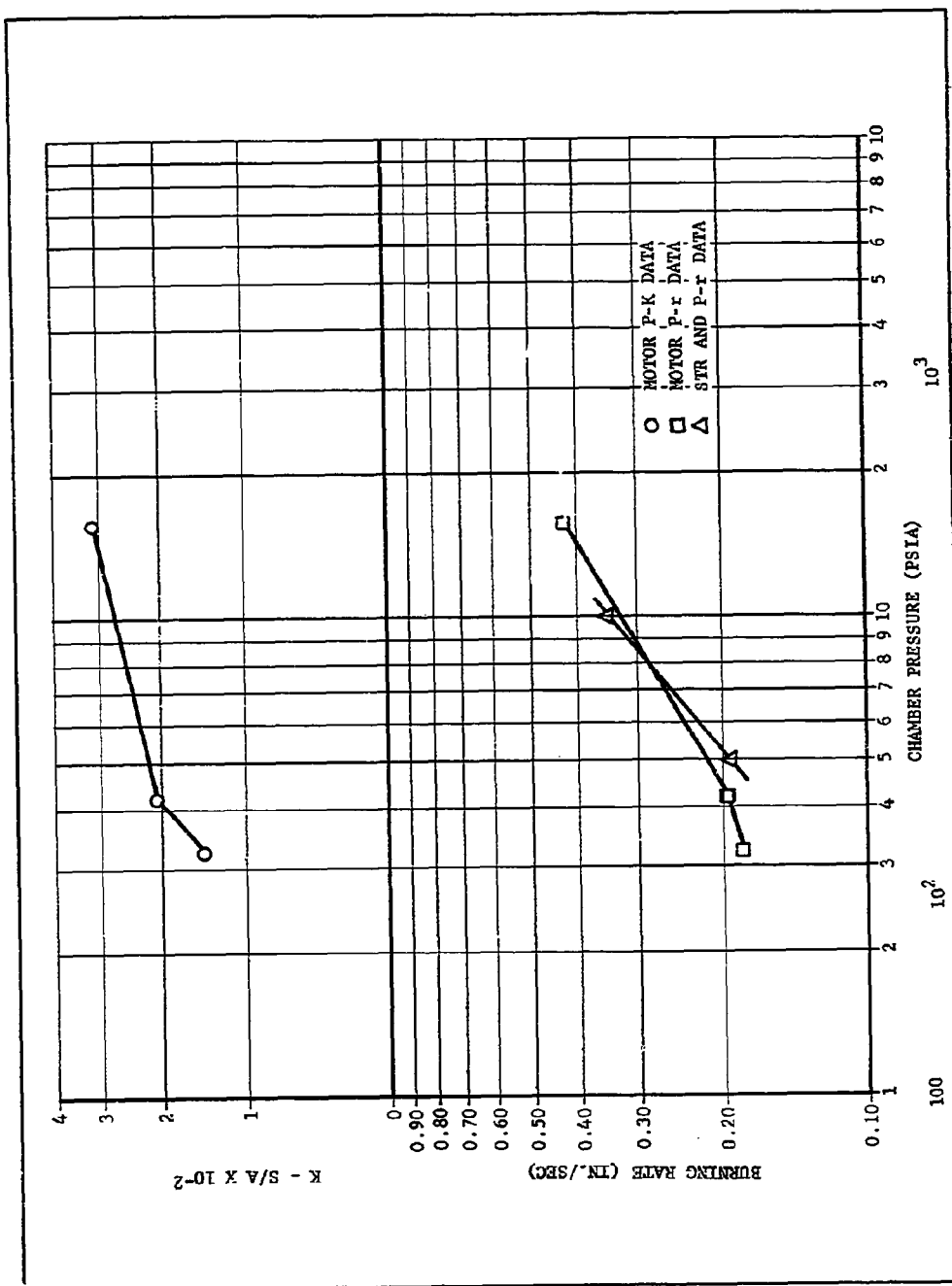
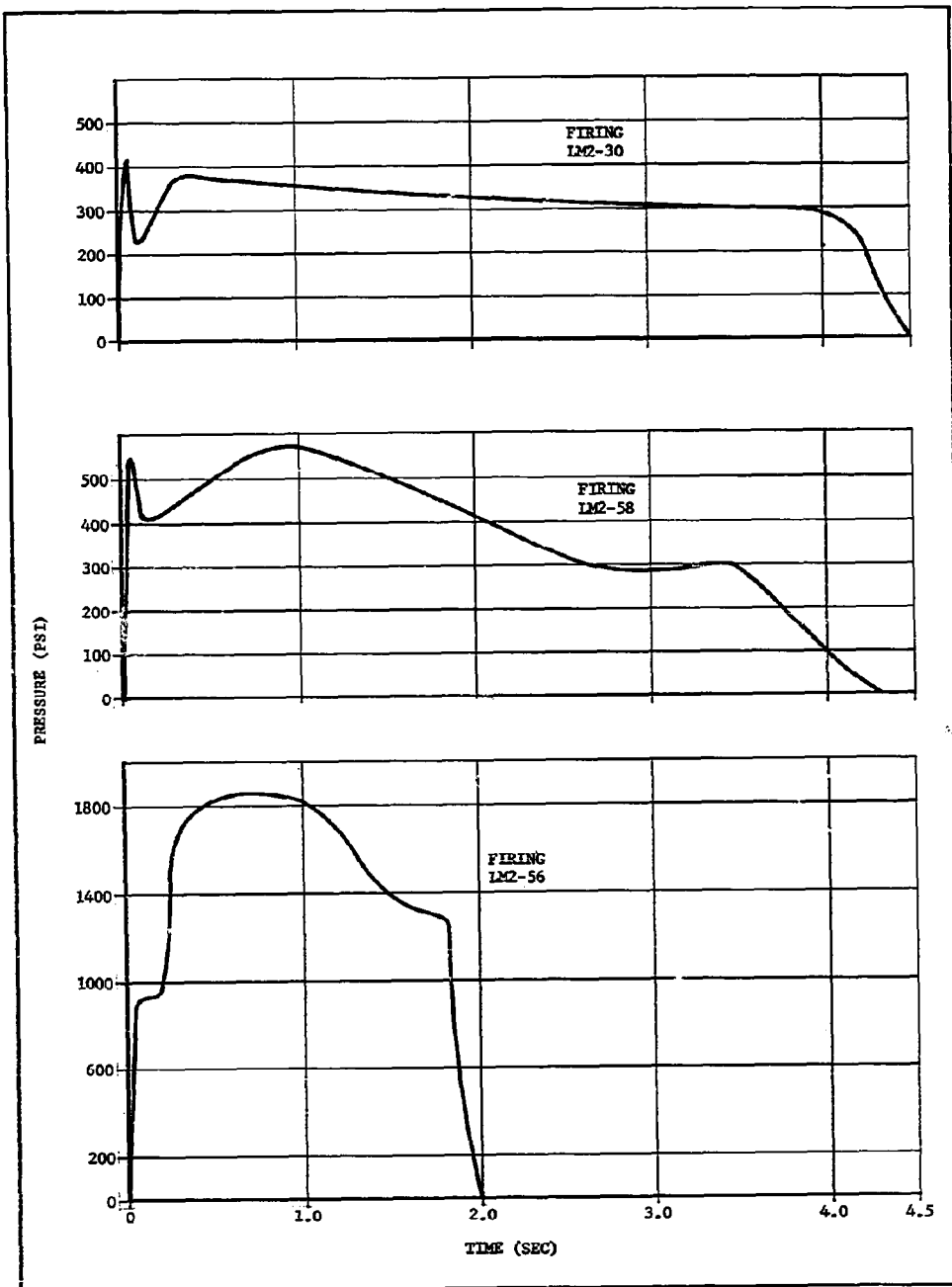Figure 9. Burning Rate and K for VIN Propellant
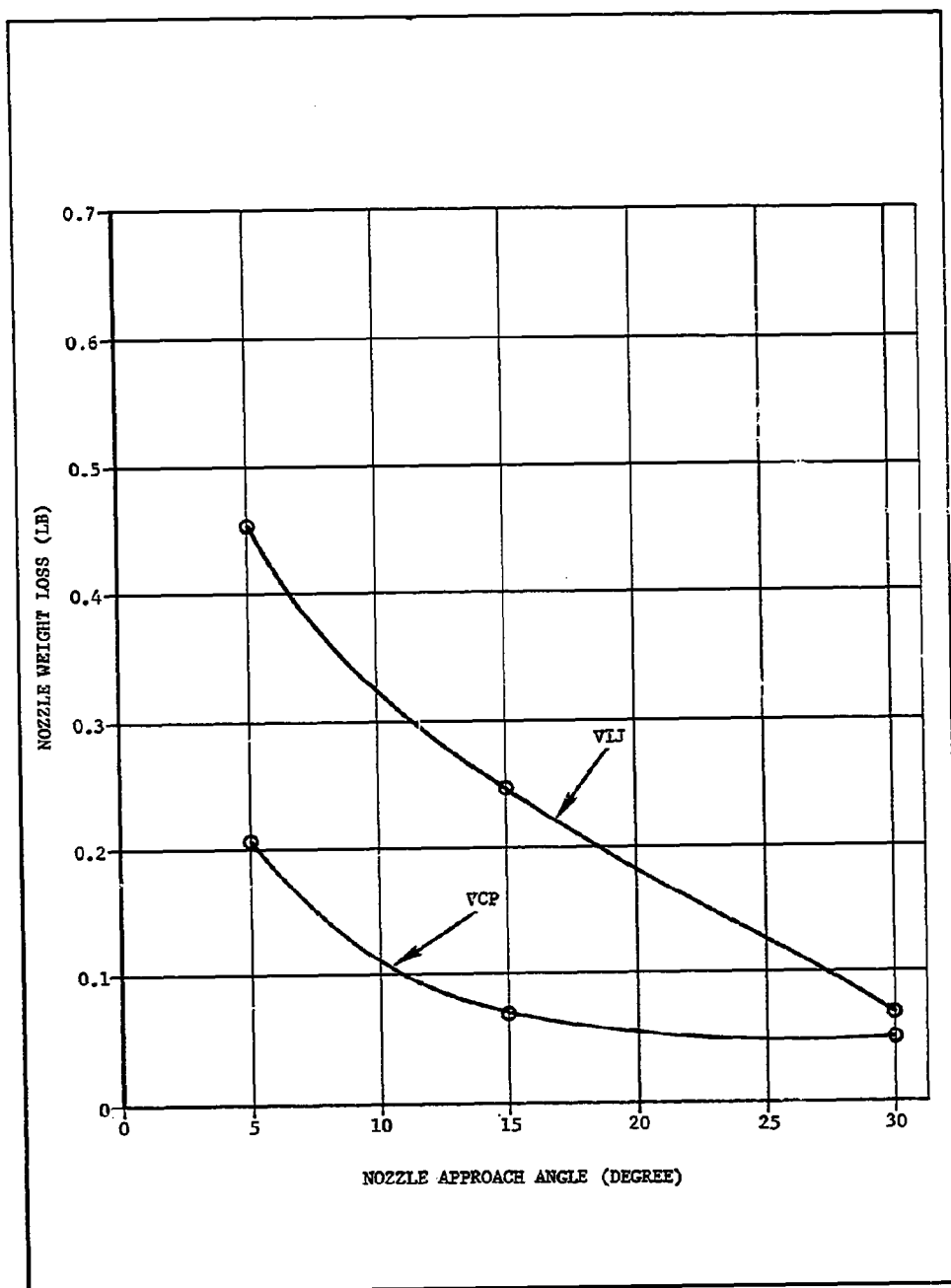
Figure 10. VIN Pressure-Time Traces

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Figure 11. Nozzle Erosion Weight Loss vs Approach Angle

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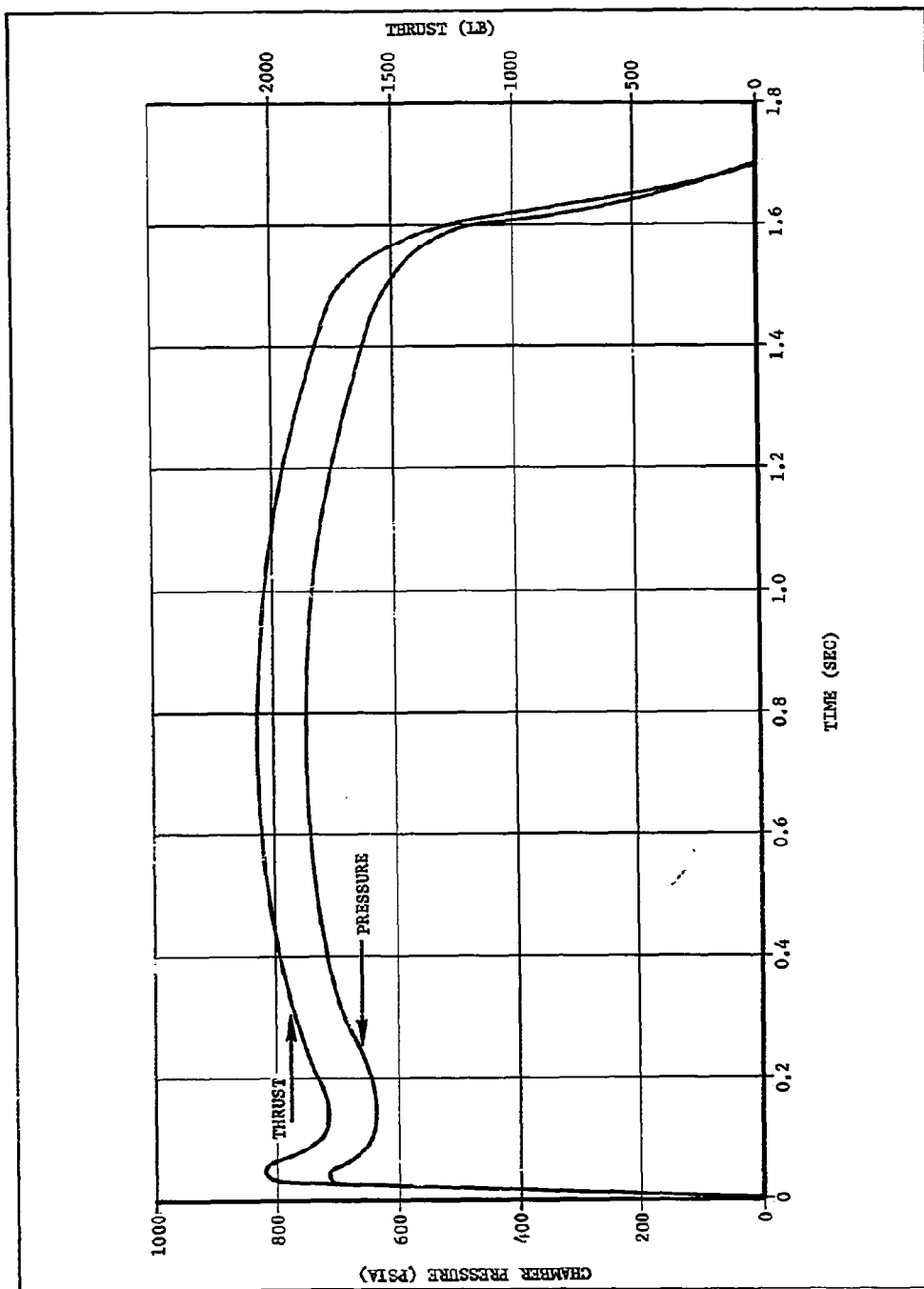Figure 12. Pressure and Thrust-Time Curves for VIY Propellant
Containing Waxed LMH-2

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3. Closed Bomb Tests

Additional results were obtained from ABL on the efficiency of LMH-2/HMX systems (VJA type). These results compared to those previously obtained for the LMH-2/AP system are contained in the following tabulation:

	LMH-2/AP				LMH-2/HMX		
% LMH-2	P_c	Particle Size (mils)	Eff	% LMH-2	P_c	Particle Size (mils)	Eff
15	1000	2.7	100	15 (VJA)	1000	3.5	96
	400	3.3	97		400	4.1	94
17 (VIY)	1000	4.1	99	17	1000	4.1	89
	400	4.5	96		400	4.8	84

As shown, the breakpoint for efficiency versus LMH-2 loading appears at approximately 15 percent for the HMX system and 17 percent for the AP system. It thus appears that both the VIY and VJA formulations will be near the optimum delivered impulse obtainable.

SECTION IV

TASK III, ADVANCED CONCEPTS

A. SCOPE

The objective of Task III is to use advanced formulation or motor techniques to study and improve LMH-2 combustion. Six LMH-2, two beryllium, and one aluminum 5-lb motor will be fired. The experiments in this task will be designed to evaluate the effect of the propellant combustion mode on performance. The task will include the following three major areas of effort:

    (1) Characterization of LMH-2

    (2) Modification of LMH-2

    (3) Fluorine addition

B. BACKGROUND

Based on the Task I correlations and theoretical calculations, two means of promoting higher efficiencies for LMH-2 propellants were originally selected for investigation under this task. The correlations showed that both decreasing the AP particle size and grinding LMH-2 would increase LMH-2 propellant efficiencies. This led to the belief that more intimate contact between the oxidizer and fuel might lead to additional performance gains. One means investigated was the pressing of LMH-2/AP binary mixtures. Work in the first quarter[1] showed pressing to be unattractive because of the poor physical properties of the pressed material and the correspondingly high pressures required for consolidation. Another means of achieving intimate contact, developed under independent research and development funding, was the recrystallization of LMH-2/AP from an AP-saturated water dispersion. Initial attempts at incorporating the AP-treated material in propellant showed a marked improvement in processibility over "as received" LMH-2. As a result, emphasis was transferred from pressing LMH-2/AP mixtures to AP treatment of LMH-2. Other methods of surface treating LMH-2 are also being investigated.

In addition to more intimate contact to improve LMH-2 performance, theoretical calculations show that in LMH-2 fluorine systems, significant amounts of BeF_2 gas are formed, which may improve thrust efficiency by reducing particle lag effects. The possibility also exists that a fluorine environment may improve LMH-2 combustion efficiency. To study these possibilities, means of introducing fluorine into LMH-2 propellants are being investigated.

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[1] Development and Test of High Energy Solid Propellants, Report No. HPC-230-12-5-1, 28 October 1965, Hercules Powder Co, Magna, Utah

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.To provide support to the Task II and Task III efforts, a limited amount of work is also being done to characterize the chemical and physical properties of LMH-2 being used on this and associated contracts.

C. CHARACTERIZATION OF LMH-2

During this report period five new LMH-2 lots were evaluated. The first two were designated as 95 and 95A and were received for motor evaluation work on Contract AF 04(611)-10742. Lot 95A differs from 95 only in that 95A was ball milled (ground). Data obtained from testing of these lots is included in this report to provide added information on LMH-2 characterization.

The third and fourth lots (96 and 97) were received for use on this contract. Received were 24 lb of lot 96 and 20 lb of lot 97. The first three lots were high purity LMH-2 (~96 percent) whereas lot 97 was less pure (~94 percent). Table XIV summarizes analyses of these lots, along with the previously evaluated lot 93. All lots were baked 4 hr at 100° C prior to shipment. The analyses provided by Ethyl Corporation represent analyses on the material prior to the vacuum baking operation. Micromerograph plots are shown in Figure 13. As shown, lots 95A, 96, and 97 had very similar particle size distributions, but lot 93 had a much smaller distribution.

A comparison of the viscosity of lots 93, 95A, and 96 in the VIX formulation is shown in Figure 14. Lots 93, 96, and 97 are compared in the VJA formulation in Figure 15. As noted from these two figures, all lots differed markedly in their processibility characteristics. However, no correlation between chemical content, specific surface area, density, or particle size distribution with processibility was evident. The processing variance from lot to lot of LMH-2 remains a serious problem. Additional evaluation of the surface character of LMH-2 is needed.

D. MODIFICATION OF LMH-2

The bulk of the posttreatment effort during the report period was devoted to preparation of material for pilot-plant evaluation. The materials prepared are described in the following subparagraphs.

1. AP Treating

Approximately 30 lb of AP-treated LMH-2 were prepared in the laboratory for motor evaluation in the VIY formulation. LMH-2 lots 96 and 97 were used for this work. The material was prepared in 600 gm batches using the methods described in Report No. AFRPL-TR-66-11 in which AP is recrystallized in an LMH-2 dispersion. In addition, an 8 to 16 hr vacuum-bake cycle was applied to the "as received" LMH-2 prior to treating.

TABLE XIV

ANALYSIS OF LMH-2 LOTS

Ingredients (wt %)	Lot No.								
	95 (a)	95 (b)	95A (b)	96 (a)	96 (b)	97 (a)	97 (b)	93 (a)
LHM-2	96.4	--	--	95.5	--	94.0	--	92.6
Active Hydrogen	17.87	17.20	18.0	17.66	17.40	17.55	18.7	--
Be Metal	1.0	--	--	1.1	--	2.0	--	2.3
Be Alkyls	3.2	--	3.8	2.3	2.4	3.3	4.8	3.1
Be Alkoxides	0.14	--	0.13	0.15	0.26	0.16	0.20	0.15
Total Chlorides	0.11	--	0.10	0.16	0.14	0.22	0.35	0.42
Volatiles	0.01	--	0.20	Nil	0.22	--	1.7	0.09
Particle Size (μ)	--	37.5	28	--	25	--	25	11
Surface Area (m^2/gm)	--	0.918	1.56	--	1.39	--	2.20	--
True Density (gm/cc)	0.64	--	--	0.64	--	0.64	--	0.63

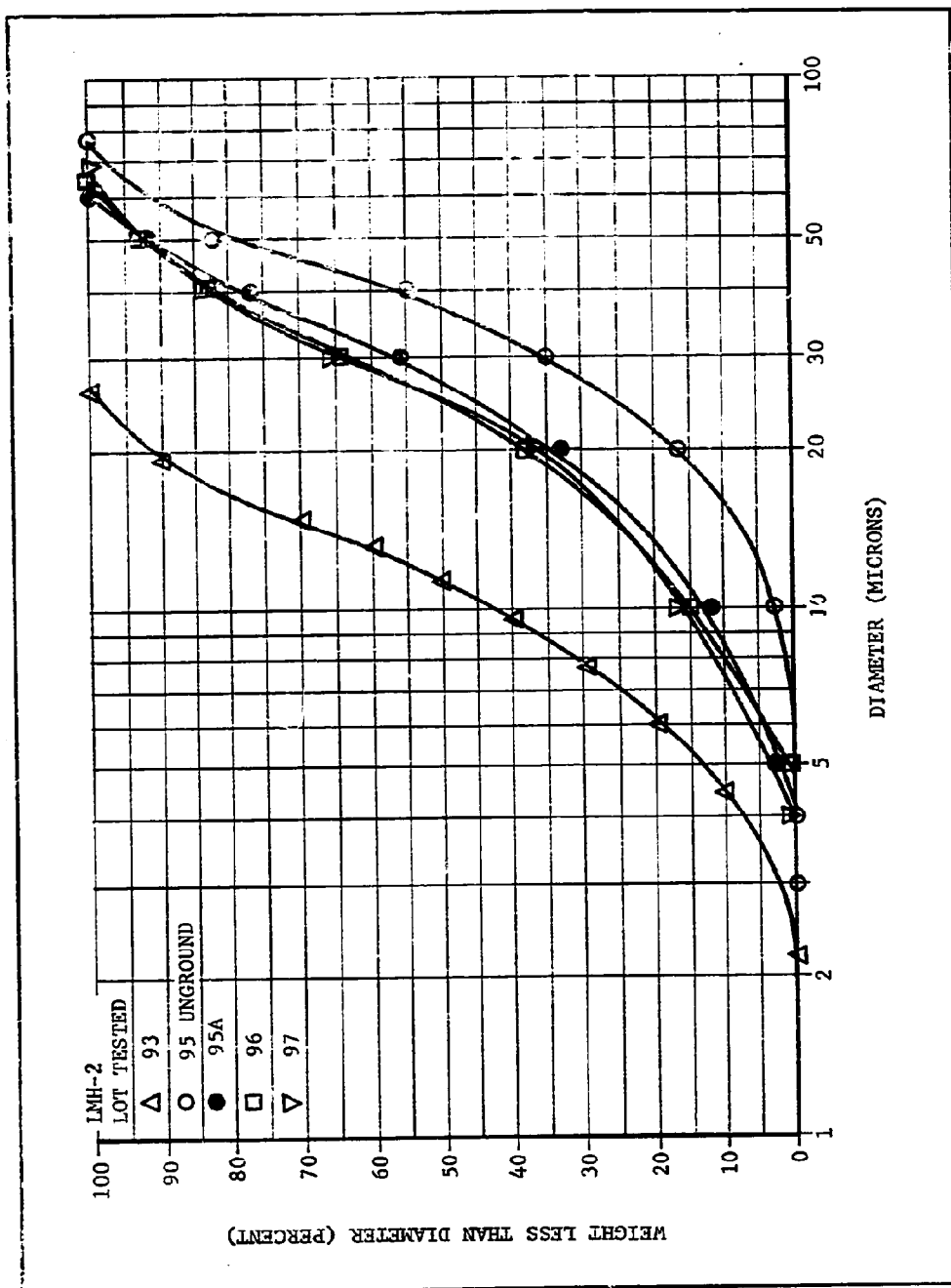(a) Analyzed by Ethyl
(b) Analyzed by Bacchus

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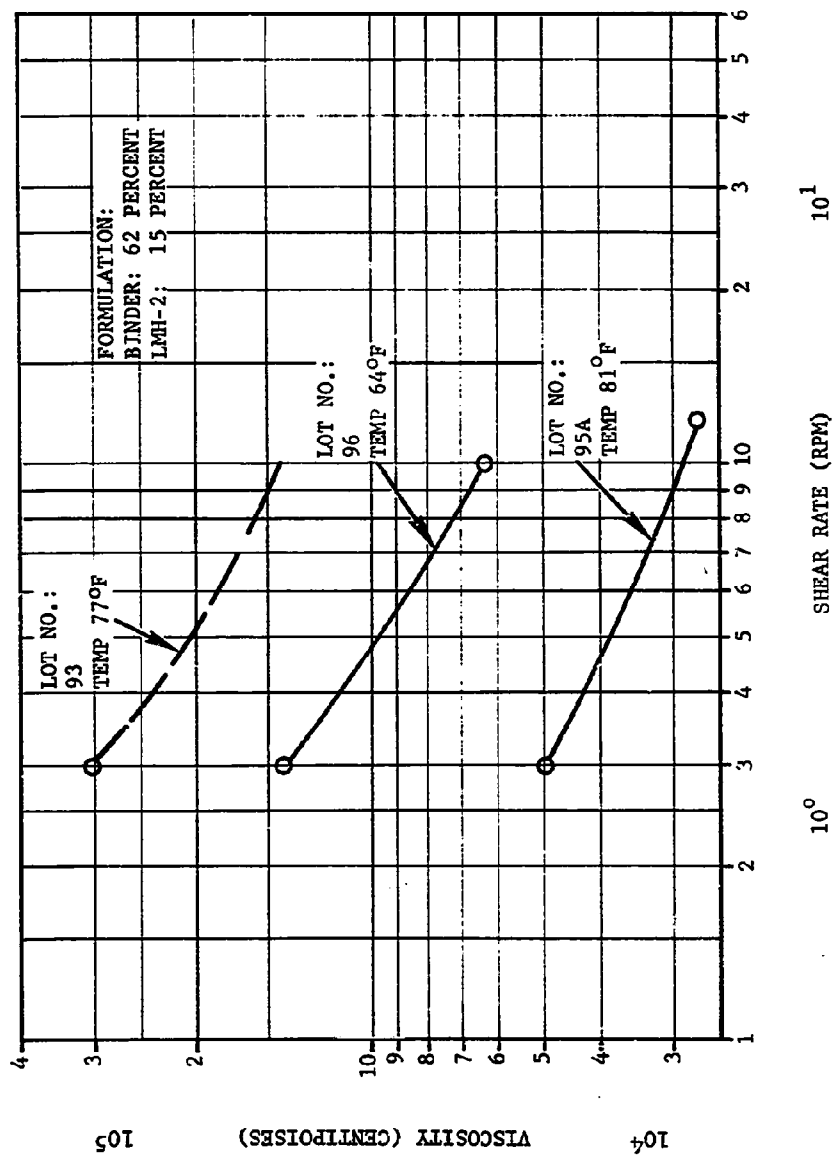Figure 13. Particle Size Distribution Analysis for LMH-2
Lots by Micromerograph

Figure 14. Viscosity as a Function of Shear Rate for
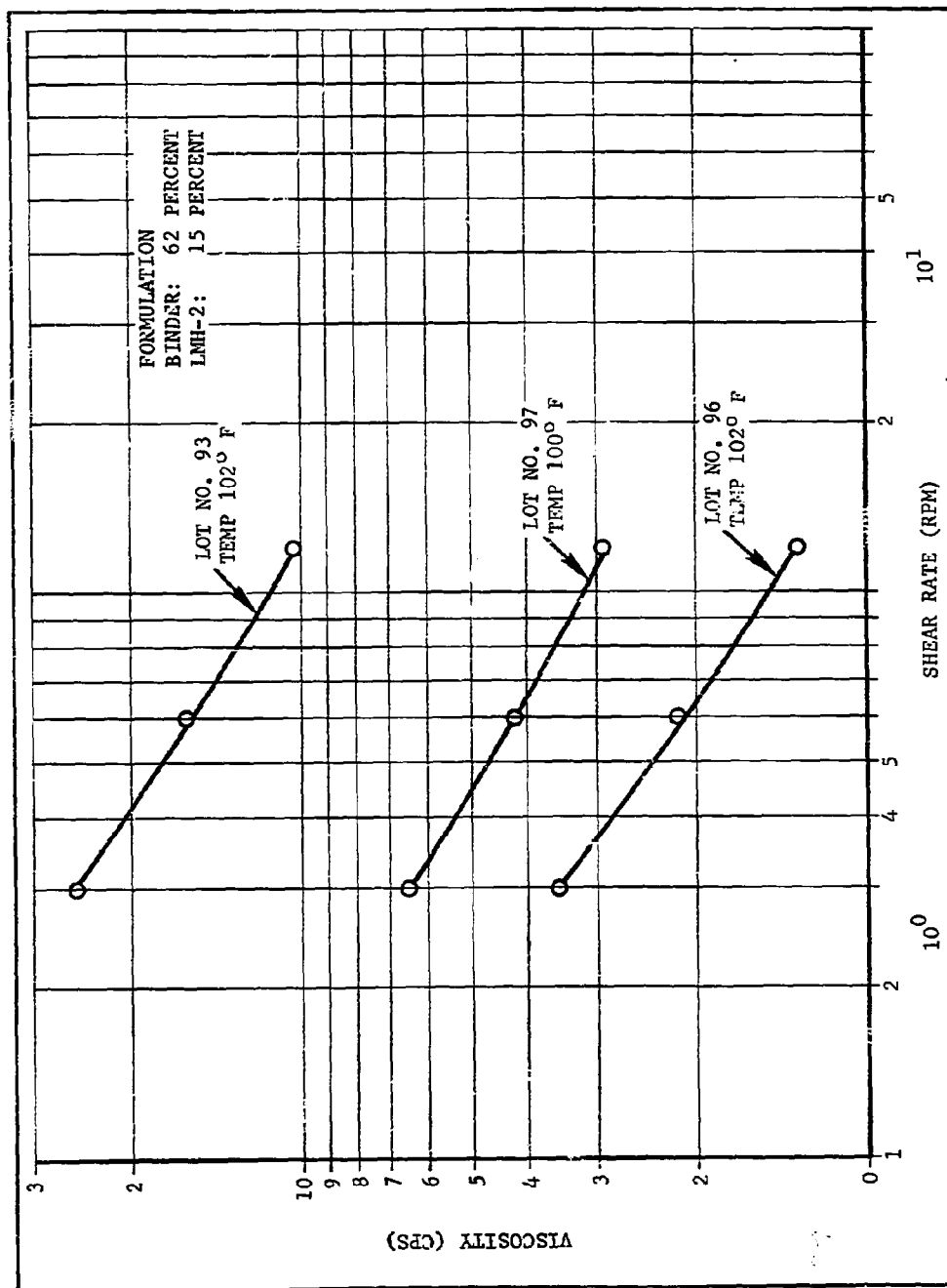Various Ball-Milled IMH-2 Lots in VIX Propellant

Figure 15. Viscosity as a Function of Shear Rate for Various
Ball-Milled LMH-2 Lots in VJA Propellant

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2. Wax Treating

Approximately 10 lb of wax-treated LMH-2 were also prepared in the laboratory for motor evaluation in the VIY formulation. The LMH-2 was waxed in 250-gm batches by applying Consolidated Electrodynamics' high-vacuum wax No. 18792 from a volatile solvent. The same vacuum-bake cycle as used for AP treating was applied to the LMH-2 before wax treating.

E. FLUORINE ADDITION

Work was initiated during the report period on the best means of introducing fluorine into conventional LMH-2 containing double-base propellants. The first method explored was the direct addition of Teflon into a VIX-type matrix. However, small mixes showed that because of its small contact angle, the Teflon was difficult to wet and required large amounts of excess solvent to adequately incorporate. An alternate method investigated was the incorporation of the low molecular weight Viton LM. Table XV summarizes theoretical calculations performed on LMH-2, Be, and Al propellants containing Viton. As shown, at the 16- to 20-percent Viton level significant amounts of the metal fluorides are formed with all three metal fuels.

Initial formulation screening was conducted on the three fuel systems. The Viton was dissolved in solvent (NG or TA) at 120° F and incorporated into the propellant matrix. Concentrations of up to 20 percent Viton were incorporated. Table XVI summarizes the formulations made to date. For the LMH-2 and Al formulations, some disproportionation of ingredients was evident, and minor formulation changes will be required.

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TABLE XV

FLUORINE ADDITION

	IMH-2							Be	Al	
Formulation (%)										
NC	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
NG	45.0	45.0	45.0	45.0	45.0	45.0	42.5	40.0	40.0	40.0
BeH2	14.0	16.0	16.0	15.0	15.0	12.0	15.0	--	--	--
Be	--	--	--	--	--	--	--	12.0	--	--
Al	--	--	--	--	--	--	--	--	18.0	21.6
Viton IM	20.0	16.0	16.0	20.0	18.0	20.0	20.0	20.0	20.0	20.0
AP	4.0	8.0	6.0	8.5	10.5	11.5	8.5	16.0	10.0	6.4
TA	5.0	5.0	5.0	--	--	--	2.5	--	--	--
Res	1.0	1.0	1.0	0.5	0.5	0.5	0.5	1.0	1.0	1.0
2NDPA	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Theoretical Performance										
I_{sp} (1000/14.7)	283.4	289.6	291.4	292.9	296.5	286.7	288.9	276.2	254.7	249.6
T_c (°K)	2820	3036	2909	3117	3218	2194	2950	3633	3439	3377
ρ (gm/cc)	1.542	1.500	1.455	1.563	1.541	1.642	1.548	2.057	2.193	2.218
Oxidation ratio	0.935	0.997	0.915	0.984	1.017	1.129	0.950	1.032	1.089	0.960
MeO* (moles/100 gm)	0.907	0.969	1.124	0.975	1.058	0.893	0.977	1.034	0.282	0.253
MeFx*	0.319	0.254	0.255	0.322	0.257	0.161	0.322	0.265	0.092	0.267

* Concentration of primary metal oxide and metal fluoride at exit conditions

TABLE XVI

VITON FORMULATION STUDIES

			Mix No.		
	95-11	95-14	95-15	95-13	95-16
Formulation (%)					
NC	10.0	10.0	10.0	10.0	10.0
NG	45.0	45.0	42.5	40.0	40.0
LMH-2	14.0	15.0	15.0	--	--
Be	--	--	--	12.0	--
Al	--	--	--	--	18.0
Viton	20.0	20.0	20.0	20.0	20.0
AP	4.0	8.5	8.5	16.0	10.0
TA	5.0	--	2.5	--	--
Res	1.0	0.5	0.5	1.0	1.0
2-NDPA	1.0	1.0	1.0	1.0	1.0
Mix size (gm)	500	20	20	20	20
Mix temp (°F)	108	--	--	--	--
Viscosity (cps)	20,000	70,000	100,000	30,000	<10,000
Comments	Solvent pockets, some weeping	Good mix, no weeping	Good mix, no weeping	Good mix, no weeping	Poor mix, settling
Sensitivity					
Impact (cm/2Kg)	3.5 (41)*	1.0	3.5	3.5	3.5
Friction (lb @ ft/sec)	23 @ 8 (900 @ 8)	88 @ 8	88 @ 8	38 @ 8	23 @ 8
Electrostatic discharge (Joules)	5.00 (0.25)	>5.0	1.25	0.25	1.25
Autoignition (°C)	218 (223)	208	213	208	209
Taliani (mmHg @ 93° C for 24 hr)	8 (7)	21	12	11	13

*No. in ( ) indicate cured values

SECTION V

INDUSTRIAL HYGIENE

The operations involving Be were monitored to ensure compliance with industrial hygiene requirements as well as safe-handling procedures for explosives. All work areas and equipment were inspected.

All employees who performed operations involving Be were examined by a medical department physician during this reporting period. There were no unusual incidents involving Be.

Air samples were obtained during all Be operations and analyzed. The air sampling data will be forwarded to Captain Owen H. Kittilstad, Industrial Hygiene Officer, Edwards Air Force Base, California.

SECTION VI

FUTURE WORK

Work to be accomplished during the next report period will include the
following:

(1) Casting and firing of the remaining 15PC motors of the
beryllium analog formulations along with the beryllium
motors for the L* evaluation

(2) Casting and firing of the 15PC motors of VIY for the L*
evaluation as well as the VIX, VJA, and VIZ formulations

(3) Casting and firing of Al, Be, and IMH-2 5PC motors for the
fluorine addition studies

(4) Additional work on the characterization and modification
of IMH-2

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

Conclusions drawn and recommendations made as a result of work done during this report period are as follows:

(1) The impulse efficiency of beryllium propellants was found to be dependent on both flame temperature and oxidation ratio. High efficiencies at high metal levels (15.5 percent Be) can be achieved by maintaining a high oxidation ratio and high flame temperature.

(2) Efficiency losses of 0.3 to 0.9 percent were observed for high-metal (14 to 15.5 percent Be) propellants containing AP as the primary oxidizer when the pressure was decreased from 1000 to 500 psia. No efficiency losses were obtained with low-metal (10 to 12 percent Be) propellants containing the mixed oxidizer, AP/HMX. Propellants showing efficiency losses with pressure also showed strong L* effects on efficiency. Additional data analysis must be made before the loss in efficiency with decreasing pressure is understood.

(3) Additional testing must be preformed to clarify the effect on efficiency of increasing L*.

(4) Initial testing of the VIY formulation containing 17 percent LMH-2 resulted in delivered impulses within 1 sec of the program objective. The wax-treated LMH-2 gave a 1 percent higher efficiency than AP-treated LMH-2 in the VIY formulation.

(5) Significant amounts of adsorbed air were found to be released from "as-received" LMH-2 with exposure to NG under vacuum conditions during the process cycle. Elimination of the majority of this air is necessary to produce nonporous grains. Vacuum baking for extended periods (16 hr at 100° C) was also found to be necessary to eliminate porosity.

(6) AP treating and wax treating of LMH-2 continued to be effective means of improving the processibility of propellants containing high LMH-2 loadings.

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Quality Progress Report

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
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13. ABSTRACT The objective of this contract is to conduct theoretical and experimental investigations resulting in the demonstration of beryllium hydride propellants delivering in excess of 280 lbf-sec/lbm at standard conditions.

Results of 15-lb beryllium motor firings confirm earlier correlations showing high flame temperature and oxidation ratio to be significant factors in obtaining good efficiencies with beryllium propellants. Decreasing nozzle approach angle and reducing AP particle size were also found to improve the efficiency of beryllium propellants.

Initial firings of LMH-2 propellants containing 17 percent LMH-2 gave delivered Isp_{1000}^{15} values of 275.4 for AP-treated LMH-2 and 278.6 for wax-treated LMH-2.

Vacuum baking and air desorption were found to be necessary to eliminate porosity of LMH-2 propellants. AP treating and wax treating of LMH-2 continued to be effective for improving the processibility of LMH-2 propellants.

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